BENTHIC MONITORING IN THE SACRAMENTO-SAN JOAQUIN DELTA
Results From 1975 Through 1981

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Chapter 1. INTRODUCTION AND MONITORING SCHEDULE

This report contains a summary of the results of the Department of Water Resources benthos monitoring program from 1975 through 1981. Some preliminary results from 1982 are also discussed. The last detailed study on benthos of the Sacramento-San Joaquin Delta estuarine ecosystem was published by the Department of Fish and Game in 1966 (Fish Bulletin 133: Ecological Studies of the Sacramento-San Joaquin Estuary, Part I). Various hypotheses are offered here to explain certain observations, but it remains to future studies to test these ideas.

This report examines the general patterns of annual and regional benthos species distribution and population density trends during a 7-year period that included the worst drought in California in 100 years (1976 and 1977), as well as periods of extremely high outflows (1978, 1980, and 1982). This report discusses the role of benthos in the food web of the Delta and the response of benthic populations to environmental extremes. Salinity, current velocity, and substrate composition are important factors affecting the benthic community structure (Flint and Rabalais, 1981; Williams, 1978; Edmonds and Ward, 1979; Wildish and Kristmanson, 1979). The potential influence of water project operations on these environmental parameters is discussed, with special reference to patterns of benthos density and distribution. A review of available biological information about the dominant benthic species is also included.

History of the Monitoring Program

Between 1975 and 1979, samples were usually collected in the spring and fall at various stations in the Delta. The original, semiannual program (1975 to 1979) was valuable for revealing patterns of species distribution and population density over a broad geographic area. This area ranged from Carquinez Strait through the Delta to as far south as Mossdale. The early program facilitated refinement of sampling methodology and aided in selection of representative sites for more intensive monitoring after 1979. Figure 1 shows the water quality monitoring sites. Table 1 indicates where benthic and substrate material were collected.

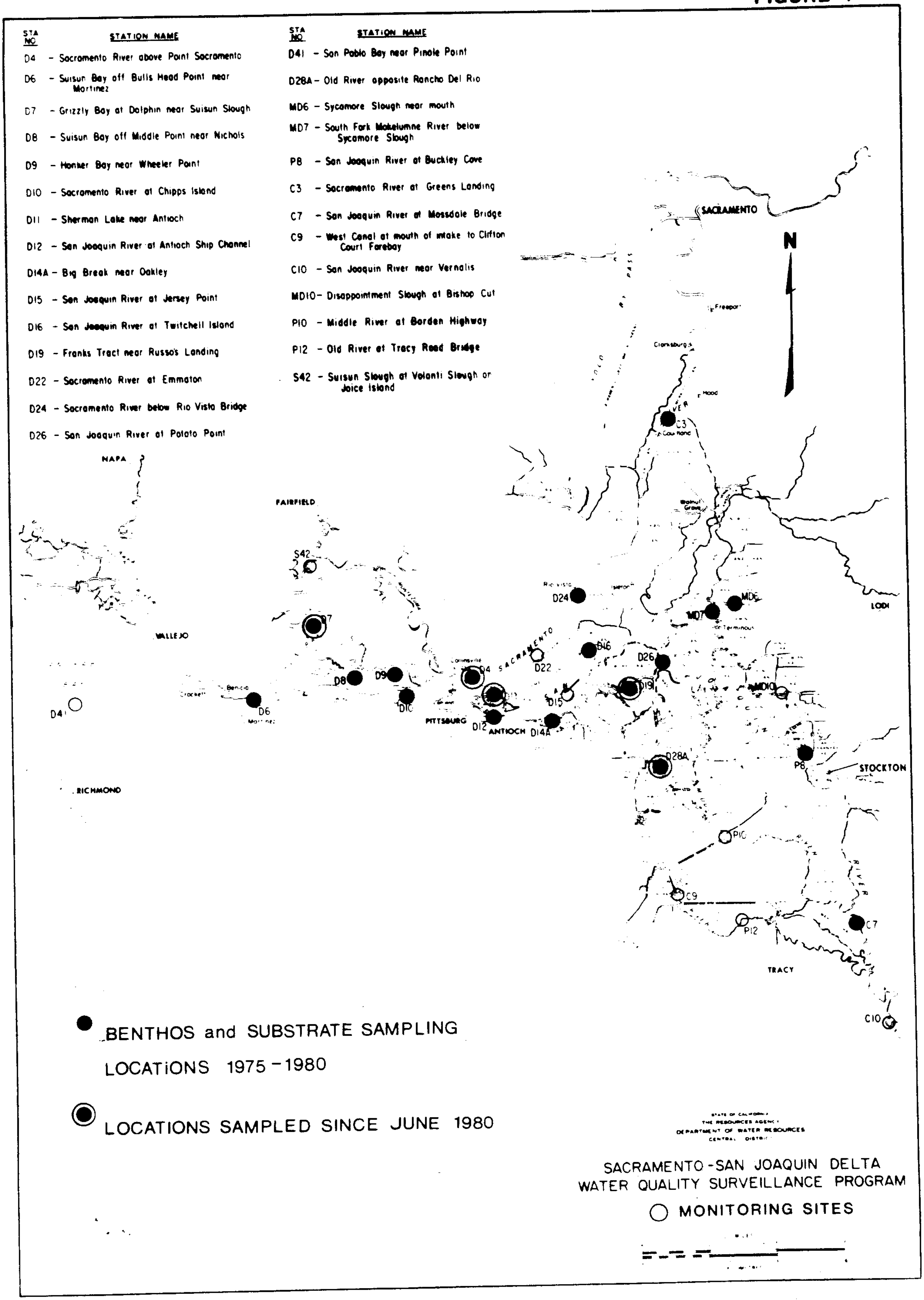
In reviewing data collected between 1975 and 1979, it became evident that semiannual monitoring was insufficient to reveal long-term ecological changes, as mandated by State Water Resources Control Board Decision 1485. Data were inadequate to determine if observed variations in seasonal and spatial abundance were due to natural factors or to operations of the water projects.

As a result of the program review, DWR designed a more intensive benthos monitoring program. The biological, chemical, and hydrological characteristics of all stations previously monitored were evaluated. Five stations were chosen to represent major aquatic environments in the Delta and estuary. Characteristics of these stations and the selection criteria are shown in Table 2. At each station, several sites were selected to represent different depths or channel locations. From June 1980 through 1981 benthos and substrate have been collected at the five stations every month.

Field Analysis and Sampling Procedures

Benthic samples were collected with a Ponar dredge, which grabs a substrate

FIGURE 1


STA NO — STATION NAME
D4 - Sacramento River above Point Sacramento
D6 - Suisun Bay off Bulls Head Point near Martinez
D7 - Grizzly Bay at Dolphin near Suisun Slough
D8 - Suisun Bay off Middle Point near Nichols
D9 - Honker Bay near Wheeler Point
D10 - Sacramento River at Chipps Island
D11 - Sherman Lake near Antioch
D12 - San Joaquin River at Antioch Ship Channel
D14A - Big Break near Oakley
D15 - San Joaquin River at Jersey Point
D16 - San Joaquin River at Twitchell Island
D19 - Franks Tract near Russo's Landing
D22 - Sacramento River at Emmaton
D24 - Sacramento River below Rio Vista Bridge
D26 - San Joaquin River at Potato Point
D41 - San Pablo Bay near Pinole Point
D28A - Old River opposite Rancho Del Rio
MD6 - Sycamore Slough near mouth
MD7 - South Fork Mokelumne River below Sycamore Slough
P8 - San Joaquin River at Buckley Cove
C3 - Sacramento River at Greens Landing
C7 - San Joaquin River at Mossdale Bridge
C9 - West Canal at mouth of intake to Clifton Court Forebay
C10 - San Joaquin River near Vernalis
MD10 - Disappointment Slough at Bishop Cut
P10 - Middle River at Borden Highway
P12 - Old River at Tracy Road Bridge
S42 - Suisun Slough at Volanti Slough or Joice Island
SACRAMENTO
N
NAPA
FAIRFIELD
VALLEJO
RICHMOND
PITTSBURG
ANTIOCH
STOCKTON
LODI
TRACY
BENTHOS and SUBSTRATE SAMPLING LOCATIONS 1975 - 1980
LOCATIONS SAMPLED SINCE JUNE 1980
SACRAMENTO - SAN JOAQUIN DELTA
WATER QUALITY SURVEILLANCE PROGRAM
MONITORING SITES

area of about 0.057 square meters. Three replicate samples were collected at each site. A single substrate grab was also taken. Benthic samples were washed on a 30-mesh screen with 28 meshes per inch (0.595 millimeter) openings. The material remaining on the sieve was then preserved in 10 percent formalin containing rose bengal stain.

Benthic samples were delivered to a private laboratory in Newcastle, California, for specimen identification and enumeration. Data records returned to DWR reported phylum, family, genus, species, number of individuals, and life history stage of all organisms in each replicate sample. One replicate was transferred to 70 percent ethanol and returned to DWR for inclusion in a reference collection.

To convert the number of organisms counted into the number of organisms per square meter of bottom area, each species count was multiplied by 19. This factor was calculated as:

$$\frac{\text{one square meter}}{\text{area of Ponar grab in square meters}} =$$

$$\frac{1.0 \text{ m}^2}{0.053 \text{ m}^2} = 19$$

Organism densities per square meter presented in this report are calculated as the average of the values for the three replicates collected at each site for each month.

Substrate samples were delivered to the DWR Soils Laboratory at Bryte, where they were subjected to a gradation analysis according to the Manual of Testing Procedures for Soils (DWR, 1962). The proportion of gravel, sand, and fines in each sample was recorded. Samples were ignited to determine the amount of organic material in each sample. A visual description was also reported so that any large organic chunks such as peat would not bias the gradation analysis by being recorded as gravel. A detailed description of the

Table 1

SITES OF BENTHOS AND SUBSTRATE SAMPLING 1975-1981

Station	Site*	1975	1976	1977	1978	1979	1980	1981
C-3	R	B	S	S	S/B	S/B		
	C	B	S/B	S/B	S/B	S/B		
	L	B	S	S	S/B	S/B		
C-7	R	S	S/B	S/B	S			
	C	S/B	S/B	S/B	S/B			
	L	S	S/B	S/B	S			
D-4	R	S	S	S/B	S/B	S/B	S/B	S/B
	C	S/B	S/B	S/B	S/B	S/B	S/B	S/B
	L	S	S	S/B	S/B	S/B	S/B	S/B
D-6	R	S/B	S/B	S/B	S			
	C	S/B	S/B	S/B	S/B			
	L	S/B	S/B	B	S			
D-7	R			S/B	S	S		
	C			S/B	S/B	S/B	S/B	S/B
	L			S/B	S	S	S	S
D-8	R	S	S					
	C	S/B	S/B					
	L	S	S					
D-9	R			B	S/B	S		
	C			S/B	S/B	S/B		
	L					S		
D-10	R	S	S/B					
	C	S/B	S/B					
	L	S	S/B					
D-11	R		S/B	S/B	S/B	S	S	S
	C		S/B	S/B	S/B	S/B	S/B	S/B
	L		S/B	S/B	S/B		S	S
D-12	R	S	S					
	C	S/B	S/B	B				
	L	S	S					
D-14A	R	S	S/B	S/B	S	S		
	C	S/B	S/B	S/B	S/B	S/B		
	L	S	S/B	S/B	S	S		
D-19	R			S	S/B	S	S	S
	C			S/B	S/B	S/B	S/B	S/B
	L			S	S/B	S	S	S
D-24	R	S	S	S				
	C	S/B	S/B	S/B				
	L	S	S	S				
D-26	R	S	S/B	S				
	C	S/B	S/B	S/B				
	L	S	S/B					
D-28A	R	S/B	S	S/B	S/B	S/B	S/B	S/B
	C	S/B	S/B	S/B	S/B			
	L	S	S	S/B	S/B	S/B	S/B	S/B
M-D6	R	S	S/B	S	S	S		
	C	S/B	S/B	S/B	S/B	S/B		
	L	S	S/B	S	S	S		
M-D7	R	S	S	S/B	S/B	S/B		
	C	S/B	S/B	S/B	S/B			
	L	S	S	S/B	S/B	S/B		
P-8	R	S	S	S	S/B	S/B		
	C	S/B	S/B	S/B	S/B			
	L	S/B	S	S	S/B	S/B		

S = Substrate Collected; B = Benthos Collected

* Facing downstream: R = Right Bank, C = Center, L = Left Bank

Table 2

CHARACTERISTICS OF FIVE MONTHLY BENTHIC SAMPLING STATIONS

Station Name and Number	Average Depth (Feet)*	Comparative Current Velocity	Salinity Range	Substrate Composition	Selection Criteria
Grizzly Bay at Dolphin (D-7)	7	Slow	Highly variable. EC may range from 200 to 20,000 uS/cm in a year. May vary by one order of magnitude within a month.	Very stable. 8% organic material and 99% fines (silt and clay) typical.	This large, shallow embayment of Suisun Bay is subject to the seasonal influence of downstream saline water and upstream freshwater outflow. Chosen for extreme salinity fluctuations.
Sacramento River above Pt. Sacramento (D-4)	38 (C) 11 (L&R)	Very Rapid Moderate	Freshwater outflow winter through spring. Salinity increases summer through fall. EC ranges from 200 to 8,000 uS/cm.	Center channel scoured; mostly sand. Banks variable. Mixed composition of sand, fines, and organic material.	Selected for effects of high current velocities on benthic fauna and for comparison of deep channel to bank conditions.
Sherman Lake near Antioch (D-11)	8	Slow	Variable, but EC generally remains below 3,000 uS/cm.	Stable. 70% fines and 8% organics typical. Edges contain more sand.	Large shallow flooded tract removed from high channel velocities. Seasonally brackish, but more stable than D-7.
Franks Tract (D-19)	8	Slow	Stable. EC rarely above 500 uS/cm.	Very stable. High in fines and organic material. Edges have more coarse substrate.	Shallow, flooded tract. Chosen for freshwater environment.
Old River Opposite Rancho del Rio (D-28A)	18	Rapid to moderate on left bank. Slow to moderate on right bank.	Stable. EC rarely above 300 uS/cm.	High sand content, 60% on left bank. 70% fines and 30% sand on right bank.	Natural approach channel to Clifton Court Forebay. Chosen for potential impact by project operations.

* Average depth of water at high slack tide. C = center, R = right bank, L = left bank facing, downstream.

field and laboratory procedures is given in Water Quality Surveillance Program, Volume III (DWR, 1980 and 1981).

Water quality samples were not collected as part of the benthic program; however, water quality data for the general area and time period were available from DWR's compliance monitoring program, and some of these data are included in this report. Details of these procedures are available in Volumes I and III of DWR's annual water quality surveillance report, 1968 through 1981.

Site Characteristics

Most adult benthic invertebrates are relatively immobile; however, the immature forms of many species are planktonic. Currents may disperse life stages of the organisms over broad geographic areas of the estuary. Environmental conditions in the area where the organisms settle out affect whether they can survive and reproduce. Two of the most important factors affecting benthic species distribution and population density in the Sacramento-San Joaquin system are substrate composition and stability and salinity (Nichols, 1977). The following sections on substrate and salinity describe the physical setting for the discussion of benthic density and distribution.

Substrate Composition

Substrate particle size is indicative of net relative velocity through time. Slow currents allow deposition of the finest silt and clay particles and small pieces of organic material. The small particles, including dead plankton and other detritus, may be eaten by benthic invertebrates or used by them to construct shelters (Barnes, 1974). Slow to moderate velocities result in deposition of a mixture of silt, clay, and organic detritus and some amounts of sand. Rapid currents remove the finer sediments (scouring), leaving a characteristic substrate composed primarily of coarser sand and gravel.

Water velocity measurements are not available from the study area, but because different sized particles are deposited by different velocity regimes, relative velocities for the sampling sites can be roughly estimated by examining the substrate. Figure 2 shows typical substrate regimes from representative sites sampled semiannually between 1975 and 1979. This figure illustrates the differences in substrate composition between stations with relatively high, moderate, and slow current velocities. It also shows that while the center of a channel may be scoured, the banks often experience moderate velocities that deposit a mixed substrate.

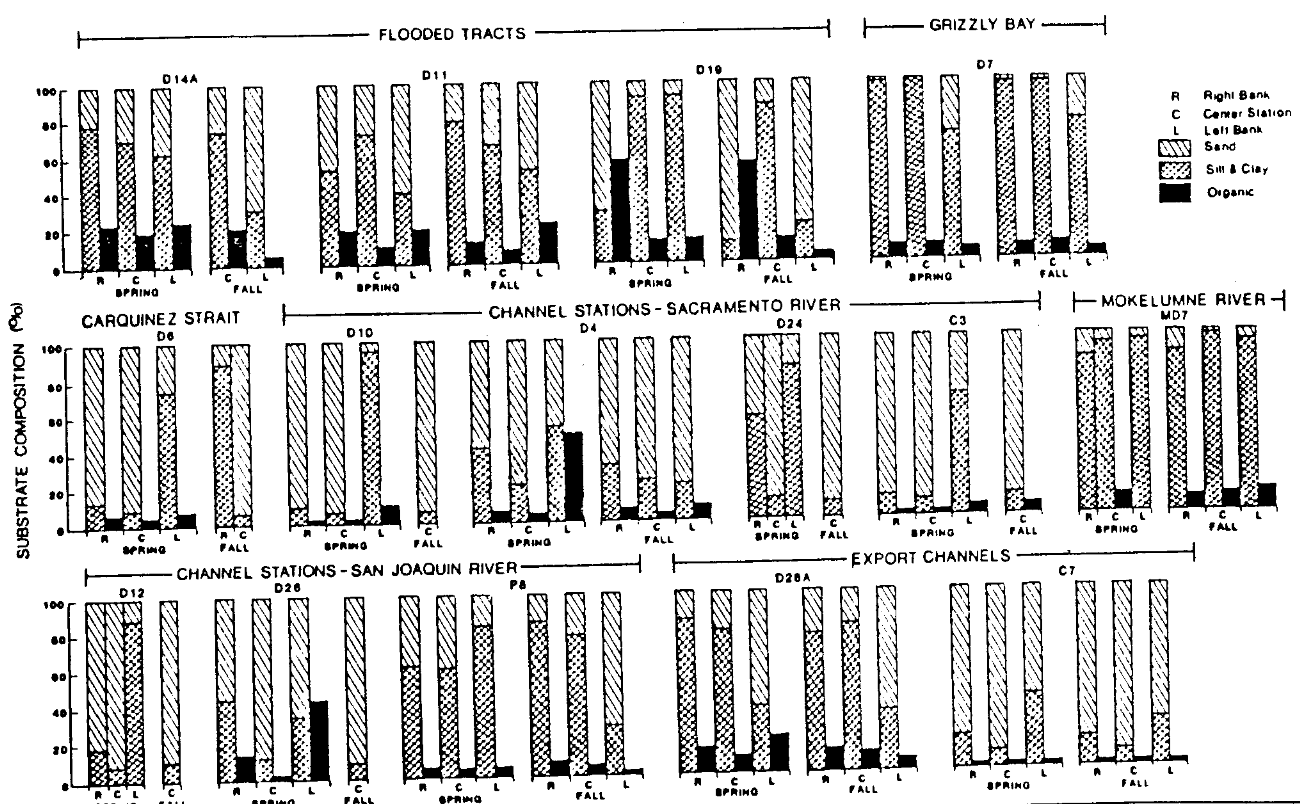
Figure 2 shows that substrate from the flooded tracts, Big Break near Oakley (D14A), Sherman Lake (D11), and Franks Tract near Russos Landing (D19), contains a high proportion of fines. Substrate from these locations typically contains up to 80 percent silt and clay and 10 to 30 percent organic material. The remains of the broken levees that surround these stations protect them from the scouring velocities of the main river channels. Deposition of high amounts of the finest sediment particles indicates these locations experience slow water velocities. Decomposition of peat banks, which form portions of the levees, and decomposing vegetation along the edges may also contribute to the high organic component of the sediments.

Grizzly Bay (D7), a large shallow embayment, also has a substrate composition typical of the slowest velocities. It is relatively isolated from the effects of high flows that sweep through the main channel between upper and lower Suisun Bay (stations D8 and D6). Substrate at Grizzly Bay normally contains more than 90 percent fines and exhibits little seasonal variation.

The channel stations, exposed to more rapid current velocities resulting from high freshwater runoff and/or tidal flows, typically have a much higher sand content (60 to 90 percent), a smaller proportion of fines (10 to 40 percent), and usually less than 5 percent organic material. Examples of these stations include: Suisun Bay off Bulls Head Point (D6), Sacramento River at Chipps Island (D10), Sacramento River above Point Sacramento (D4), Sacramento River below Rio Vista Bridge (D24), Sacramento River at Greens Landing (C3), San Joaquin River at Antioch Ship Channel (D12), and San Joaquin River at Potato Point (D26). The center channel sampling sites at these stations exhibit evidence of rapid water velocities that have scoured away all but the coarsest sand particles. The center sites are in deeper water, where flows are faster or where dredging may occur. Along the banks at these stations the substrate usually contains more fines and organic material, evidence of more moderate, depositional current velocities.

Stations in sloughs and river channels of the interior Delta tend to have substrates typical of more moderate to slow velocities. The substrate composition of these regions is similar, for the most part, to that of the protected, shallow, flooded tracts. Examples of these conditions are the South Fork Mokelumne River below Sycamore Slough (MD7), San Joaquin River at Buckley Cove (P8), and Old River opposite Rancho del Rio (D28A).

FIGURE 2. SPRING AND FALL SUBSTRATA COMPOSITION AT REPRESENTATIVE LOCALITIES SHOWING DIFFERENCES BETWEEN SITES WITH HIGH, MODERATE AND SLOW CURRENT VELOCITIES



Monthly substrate sampling at five stations since 1980 confirmed trends indicated by the earlier semiannual sampling program. Table 3 presents the range, average, and variability of the major substrate components measured at these selected stations. The flooded tracts, Sherman Lake (D11) and Franks Tract (D19), and the shallow Grizzly Bay (D7) have the most stable, predictable substrate, high in fines and organic material. This composition indicates slow to moderate current velocities. As expected from earlier monitoring results, the channel banks at Sacramento River near Point Sacramento (D4R and D4L) contain more fines and organic material than the scoured, deep water

Table 3

SUBSTRATE CHARACTERISTICS AT BENTHIC MONITORING STATIONS, JUNE 1980 THROUGH DECEMBER 1981
(19 Samples per Location)

Benthic Station	Site*	Substrate Composition: Component	Range (%)	Average (%)	Standard Error	Substrate Regime	Relative Current Velocity
Grizzly Bay (D-7)	C	Sand	0-46	8.4	3.62	Very stable and predictable through time. Periods of sand deposition during high outflow. Usually, fine sediments predominate year round.	Slow
		Fines	54-100	91.6	3.62		
		Organic	6.3-10.3	8.1	0.20		
Pt. Sacramento (D-4)	R	Sand	1-96	38.3	7.87	Quite variable; patchy composition along banks. Usually more fines and organic material than in center of channel.	Moderate to Rapid (Variable)
		Fines	3-99	61.6	7.90		
		Organic	1.4-9.3	5.2	0.64		
	C	Sand	6-94	79.2	4.64	Generally, sand is dominant through the year, with very little organic material or fines. This deep water site typifies a high velocity regime.	Rapid
		Fines	6-48	20.8	4.64		
		Organic	1.1-7.8	2.5	0.37		
	L	Sand	1-80	45.6	6.31	Similar to right bank. Somewhat more sand and organic material than right bank.	Moderate to Rapid (Variable)
		Fines	20-99	55.5	9.27		
		Organic	2.4-33.8	8.9	2.31		
Sherman Lake (D-11)	C	Sand	16-47	29.3	1.88	Moderately stable. Fairly high in fines and moderate levels of organic material, usually peat fragments.	Slow to Moderate
		Fines	53-83	67.6	3.90		
		Organic	5.6-13.5	7.0	0.23		
Franks Tract (D-19)	C	Sand	7-24	15.4	1.10	Very stable and predictable through time. High in fines and organic material. High peat content contributes to high organic fraction.	Slow
		Fines	76-93	84.3	1.12		
		Organic	10.5-14.8	11.6	0.65		
Old River Opposite Rancho del Rio (D-28A)	R	Sand	5-60	27.3	3.90	Moderately stable; similar to flooded tracts (D-11 and D-19). Occasional large increases in sand. Usually much peat in sample.	Slow to Moderate
		Fines	41-95	72.2	3.78		
		Organic	5.4-14.3	11.2	0.57		
	L	Sand	25-90	66.0	3.70	Generally, sand predominates, but fines are sometimes abundant. More sand compared to right bank.	Rapid to Moderate
		Fines	10-75	33.4	3.76		
		Organic	1.0-12.2	5.0	0.61		

* Facing downstream: R = Right Bank, C = Center, L = Left Bank

center channel (D4C). Old River opposite Rancho del Rio (D28A) is in an approach channel to Clifton Court Forebay at the State Water Project's Harvey O. Banks Delta Pumping Plant. Although both the left and right bank sites (D28AL and D28AR) have substrate compositions typical of moderate velocities, the left bank usually has a higher sand content than the right bank.

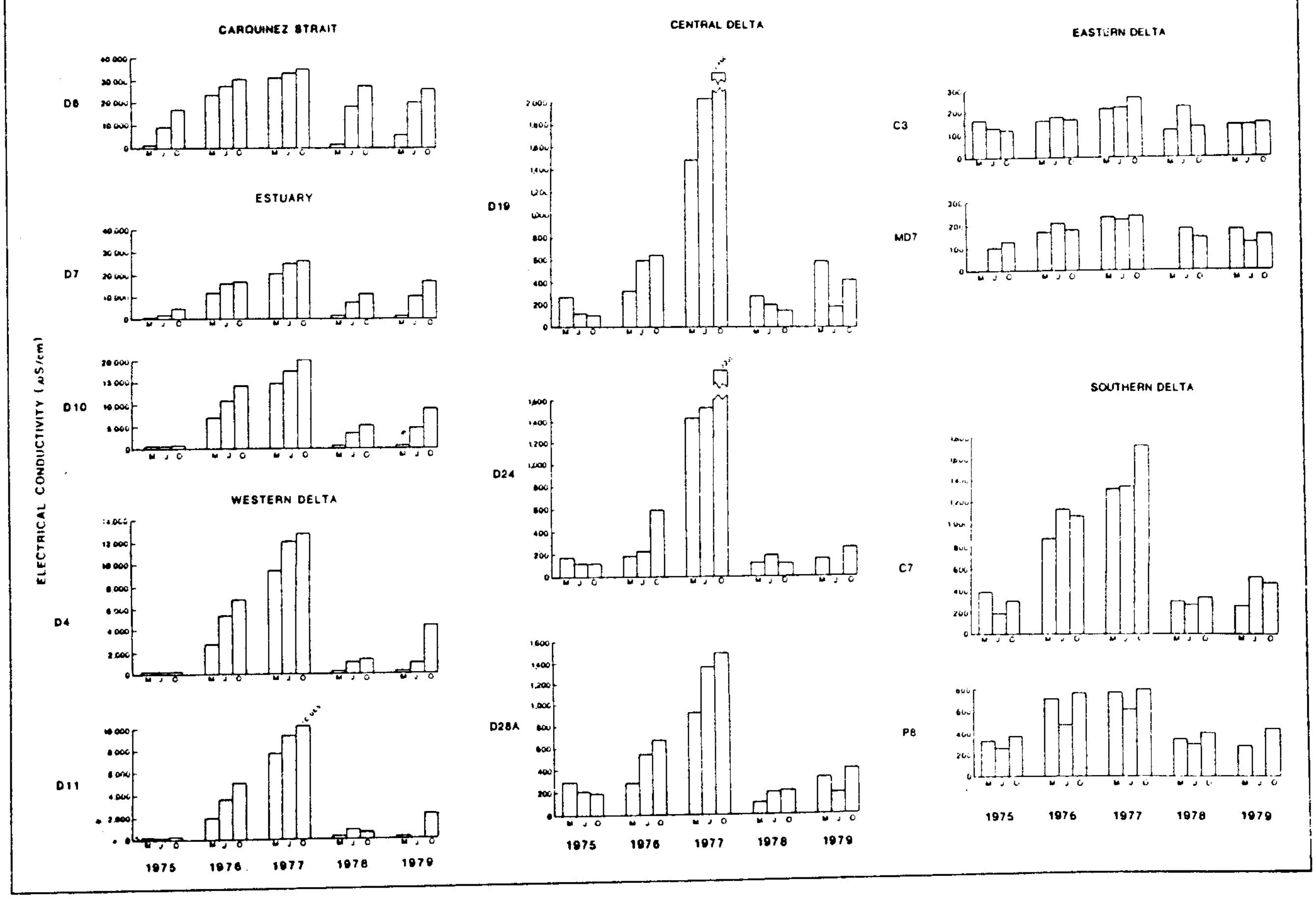
Salinity

Salinity is another factor that has a significant influence on distribution and density of the relatively sedentary benthic species. The organisms must either be able to tolerate salinity fluctuations, utilize microhabitats that are protected from rapid changes such as burrows deep in the substrate, move to areas within their tolerance limits, or restrict their distribution to areas with highly predictable salinity regimes. The aquatic environment of the benthos study area experiences a wide range of salinity, from fresh to brackish water. Electrical conductivity (EC) measurements taken during regular water quality sampling trips are used as an indication of the general salinity regime at each benthic station.

Seasonal or annual changes in freshwater outflow greatly affect the salinity gradient throughout the sampling area. Figure 3 summarizes the annual pattern of EC at selected stations where benthos were monitored from 1975 to 1979. The stations in Figure 3 represent typical patterns of seasonal salinity change and show the difference between wet and dry years in different regions of the monitoring area.

FIGURE 3

MEAN ELECTRICAL CONDUCTIVITY FOR MARCH, JUNE AND OCTOBER 1975-1979

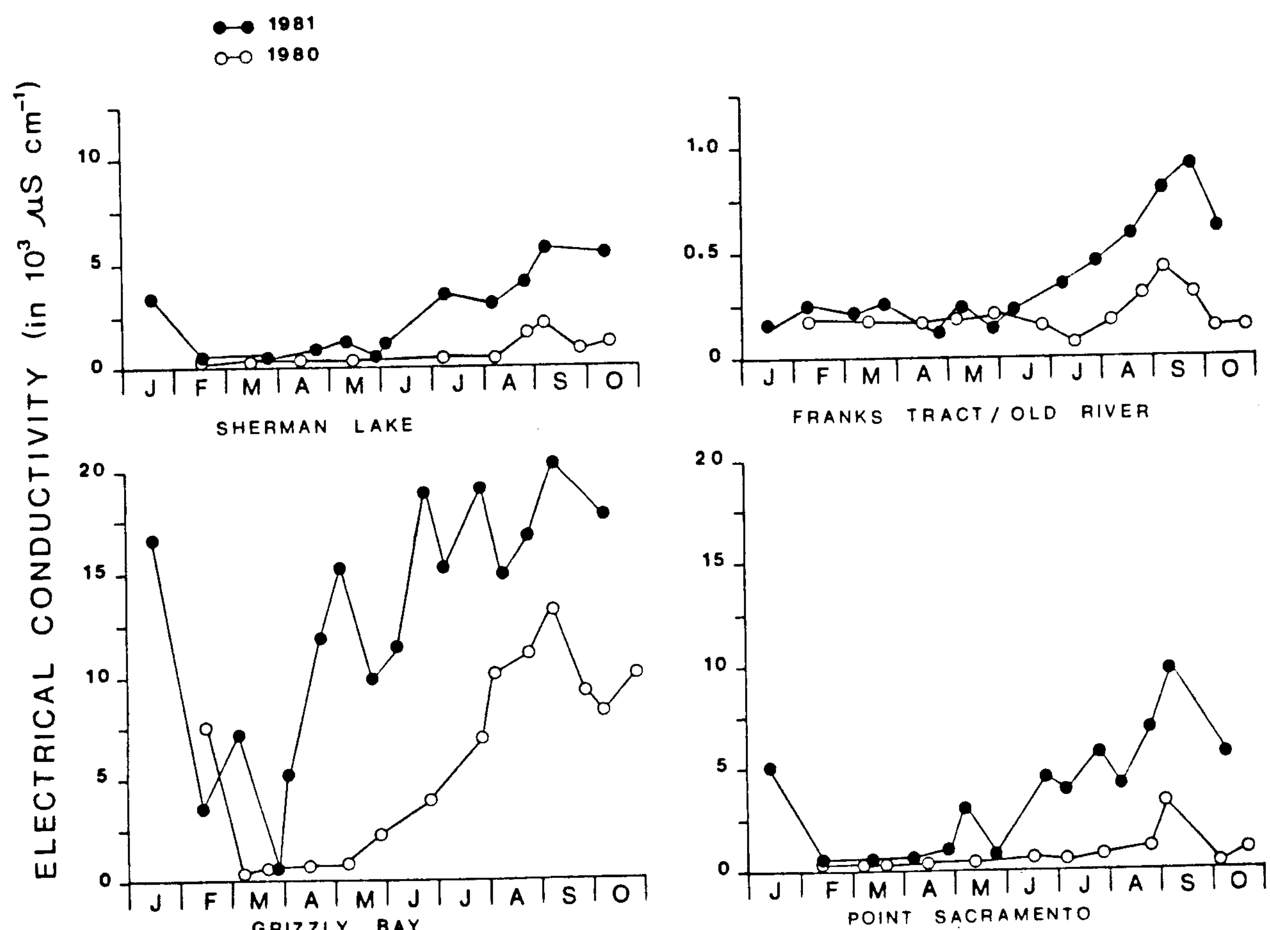


Most stations experience an increase in salinity as the year progresses and outflows decrease. At the western stations, the influx of tidally driven saline waters causes a more pronounced rise in EC than at the interior Delta stations. This occurs during the daily tidal cycle as well as annually. In wet years such as 1975, 1978, and 1980, EC was lower than usual throughout the western Delta and remained lower than normal at more stations through the summer and fall. During dry years such as 1976, 1977, and 1981, much of the estuary and western Delta experienced elevated salinities for a prolonged period.

Figure 4 compares the monthly mean EC at the five benthic stations sampled during 1980 and 1981. The early, extreme rise in salinity can be seen for a dry year, 1981, when compared to a wet year, 1980, particularly for the most westerly stations. The normal January through March freshwater outflow peak was virtually absent in 1981. This allowed saline ocean water to penetrate farther upstream much earlier in the year.

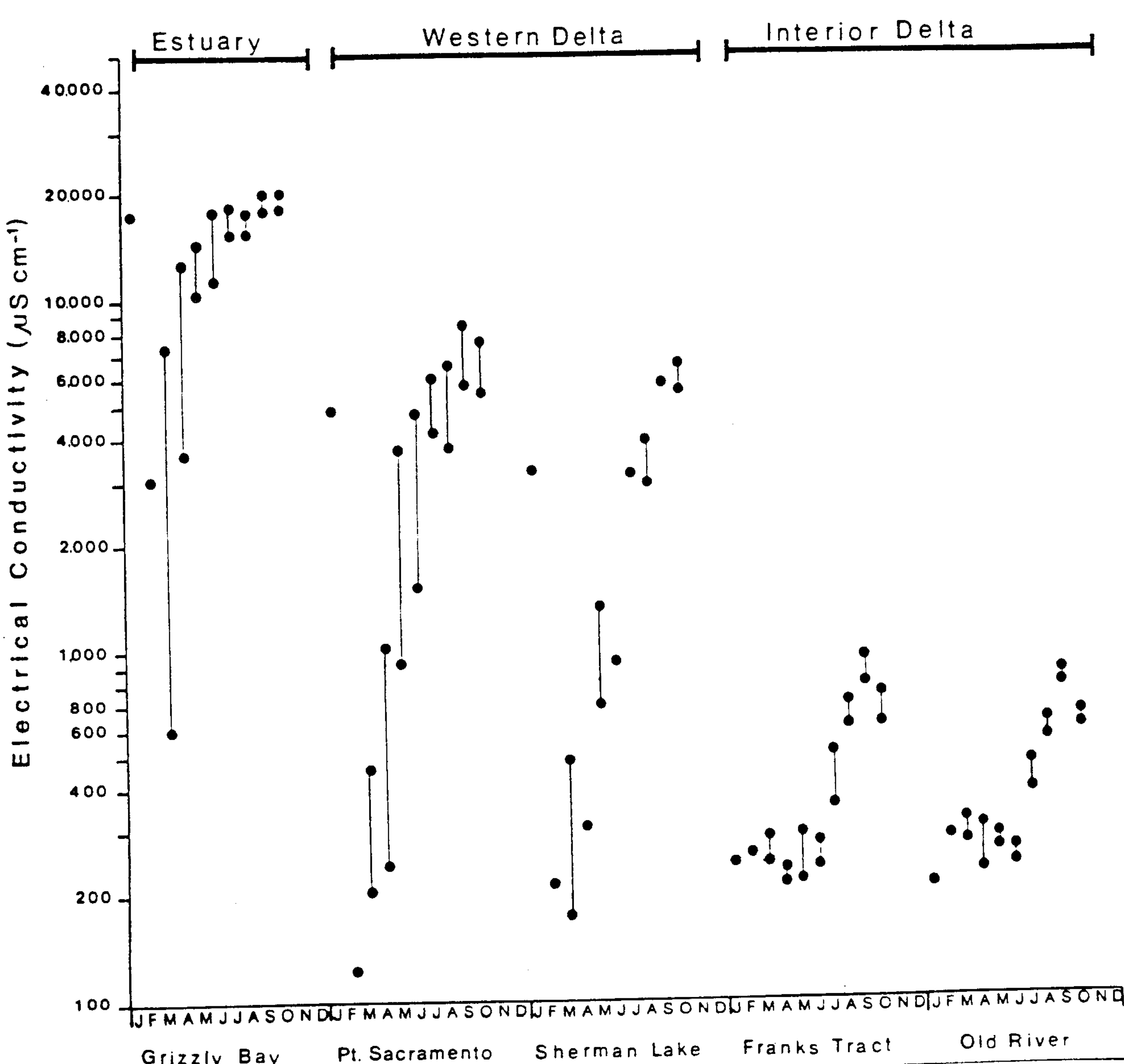
At the westerly stations, the combined influence of freshwater outflow and the tidally driven intrusion of saline water commonly creates extreme short-term salinity fluctuations. For

FIGURE 4. COMPARISON OF MONTHLY MEAN ELECTRICAL CONDUCTIVITY BETWEEN A WET YEAR (1980) AND A DRY YEAR (1981)



example, Grizzly Bay (D7) EC can vary from several hundred to several thousand microsiemens per centimeter (uS/cm) during a month (see Figure 5). Point Sacramento (D4) and Sherman Lake (D11) experience more moderate seasonal salinity fluctuations when freshwater outflows decrease (see Figure 4), but still exhibit more variable short-term salinity changes than do upstream stations. Sherman Lake's old levee system may restrict salinity intrusion from the main channel at nearby Point Sacramento (D4). The interior Delta stations (D19 and D28A) show only slight EC increases during summer and fall. This is primarily associated with the release of agricultural drainage water at this time. Even during a dry year like 1981, Figure 4 shows that ECs remained relatively low and stable at the interior Delta stations compared to those downstream.

FIGURE 5. BIMONTHLY RANGE OF ELECTRICAL CONDUCTIVITIES AT BENTHIC SAMPLING STATIONS DURING 1980



Chapter 2. COMPOSITION AND ABUNDANCE OF BENTHIC POPULATIONS

Since the benthic monitoring program began in 1975, more than 140 species of benthic invertebrates have been identified in the sampling area. Of these, only about 13 species represent 10 percent or more of the total population density at a given sampling site. Because of the large numbers of species that occur at very low densities or infrequently, this discussion focuses primarily on species usually most numerous in benthic samples. A complete list of species collected at each site is given in Appendix A.

Regional Patterns of Species Composition and Population Density

The DWR benthic monitoring program has enabled us to identify some seasonal and regional patterns of species abundance. The predominant phyla found throughout the sampling area are Annelida and Arthropoda. Several species of freshwater Mollusca also occur. The number of species found remained relatively constant through time within an area, except when environmental conditions underwent extreme fluctuations such as during the 1976-1977 drought.

The average number of species collected in different regions of the monitoring area is shown in Figure 6. Suisun Bay and the western Delta typically support the fewest species, from 3 to 7. The benthic fauna of the westernmost stations is dominated by a single mollusc, *Corbicula fluminea*; two Arthropods, *Corophium stimpsoni* and *C. spinicorne*; and annelids of the genus *Limnodrilus*. The interior, freshwater stations normally support many more species. The average is about 15, but up to 20 is not uncommon.

The density of benthic invertebrates also exhibits regional differences. Figure 7 compares the average annual densities of different regions in the monitoring area. The portion of the upper estuary (Suisun Bay in Figure 7) between Grizzly Bay (D7) and Chipps Island (D10) typically supports the lowest densities, usually averaging less than 2,000 organisms per square meter. However, during the drought, more salt-water adapted benthos moved upstream and temporarily established large populations in this area. (This is discussed further in the following section.) The southern Delta also has relatively low density benthic populations. Average densities are 5,000 organisms per square meter or less.

Brackish water reaches of the western Delta from the Sacramento River at Pt. Sacramento (D4) to Big Break near Oakley (D14A) consistently support the lowest number of species but higher average densities through time. Normally from 10,000 to 15,000 organisms per square meter are collected in this region. Average monthly densities may increase to 50,000 to 100,000 seasonally (see Figures 8 through 14). The central and eastern Delta appear to support intermediate benthic population densities, typically averaging about 5,000 to 12,000 organisms per square meter, while the number of species is typically higher compared to the western Delta. In the vicinity of Sycamore Slough and the Mokelumne River (MD6 and MD7), populations may reach much higher numbers. Monthly monitoring in selected regions since 1980 has confirmed this general regional pattern of benthic population density.

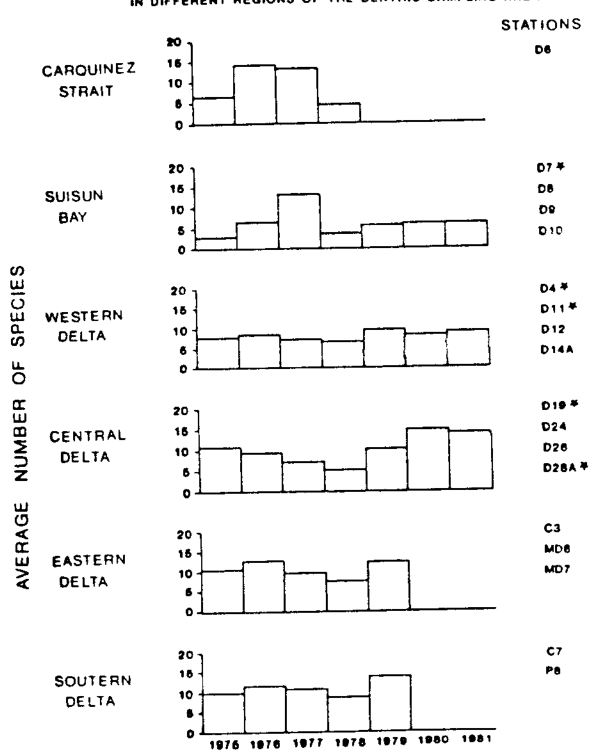
Species Distribution, Life History, and Seasonal Population Fluctuations

Euryhaline forms dominated the benthic fauna from Grizzly Bay (D7) eastward within the monitoring area (see Figures 8 through 14). These were oligochaete worms of the genus Limnodrilus, the introduced Asiatic clam Corbicula fluminea (formerly C. manilensis), and the amphipods Corophium stimpsoni and C. spinicorne. Another organism, Manayunkia speciosa, a polychaete worm, was only found at high densities east of Franks Tract (D19). Other groups of worms (Nemata, Nemertea, and Oligochaeta), aquatic insects (Chironomidae), and molluscs (Unionidae, Sphaeriidae, Tellinidae, and Myidae) were commonly collected but at low densities in different regions of the sampling area (see Appendix A).

West of Suisun Bay, at Carquinez Strait (D6), saltwater-tolerant estuarine species of molluscs and crustaceans typical of San Pablo Bay fauna are generally found (Painter, 1966). Among the most common species collected in DWR samples were the clams Mya arenaria and Macoma balthica; the polychaete worms Boccardia ligerica and Streblospio benedicti; and the amphipods Grandidierella japonica, Corophium acherusicum, and Ampelisca milleri.

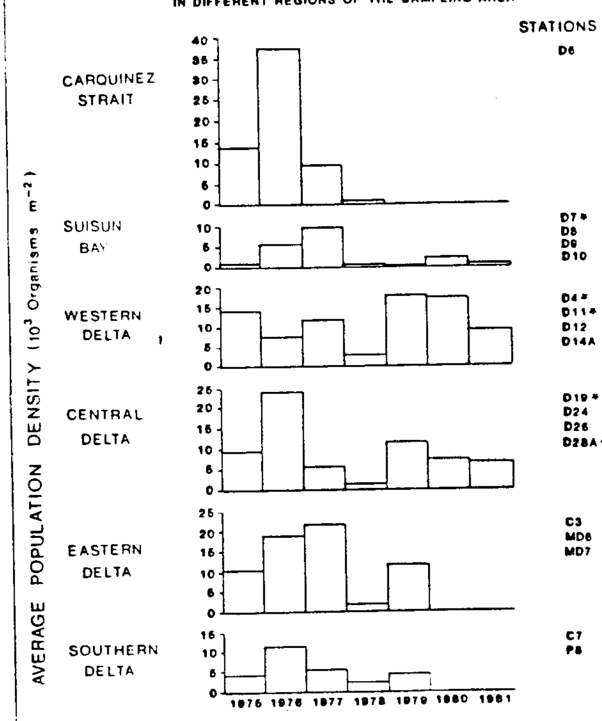
This "faunal break" west of Suisun Bay has been known for many years (Filice, 1958; Painter, 1966). The extreme salinity fluctuations within Suisun Bay probably prevent the establishment of stable, abundant populations of either the saltwater benthos from San Pablo Bay or the brackish water species found farther upstream. Saltwater benthic species are also collected occasionally in Grizzly Bay (D7) and in the western Delta below Pt. Sacramento (D4) during the fall when freshwater outflow is lowest or during dry conditions such as the 1976-1977 drought when saline water intruded upstream. These species do not remain in the upper estuary once freshwater outflows increase.

FIGURE 6. ANNUAL AVERAGE NUMBER OF SPECIES COLLECTED IN DIFFERENT REGIONS OF THE BENTHIC SAMPLING AREA



* Stations sampled monthly since June 1980

FIGURE 7. ANNUAL AVERAGE BENTHIC POPULATION DENSITY IN DIFFERENT REGIONS OF THE SAMPLING AREA



* Stations sampled monthly since June 1980

FIGURE 8. 1975 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION

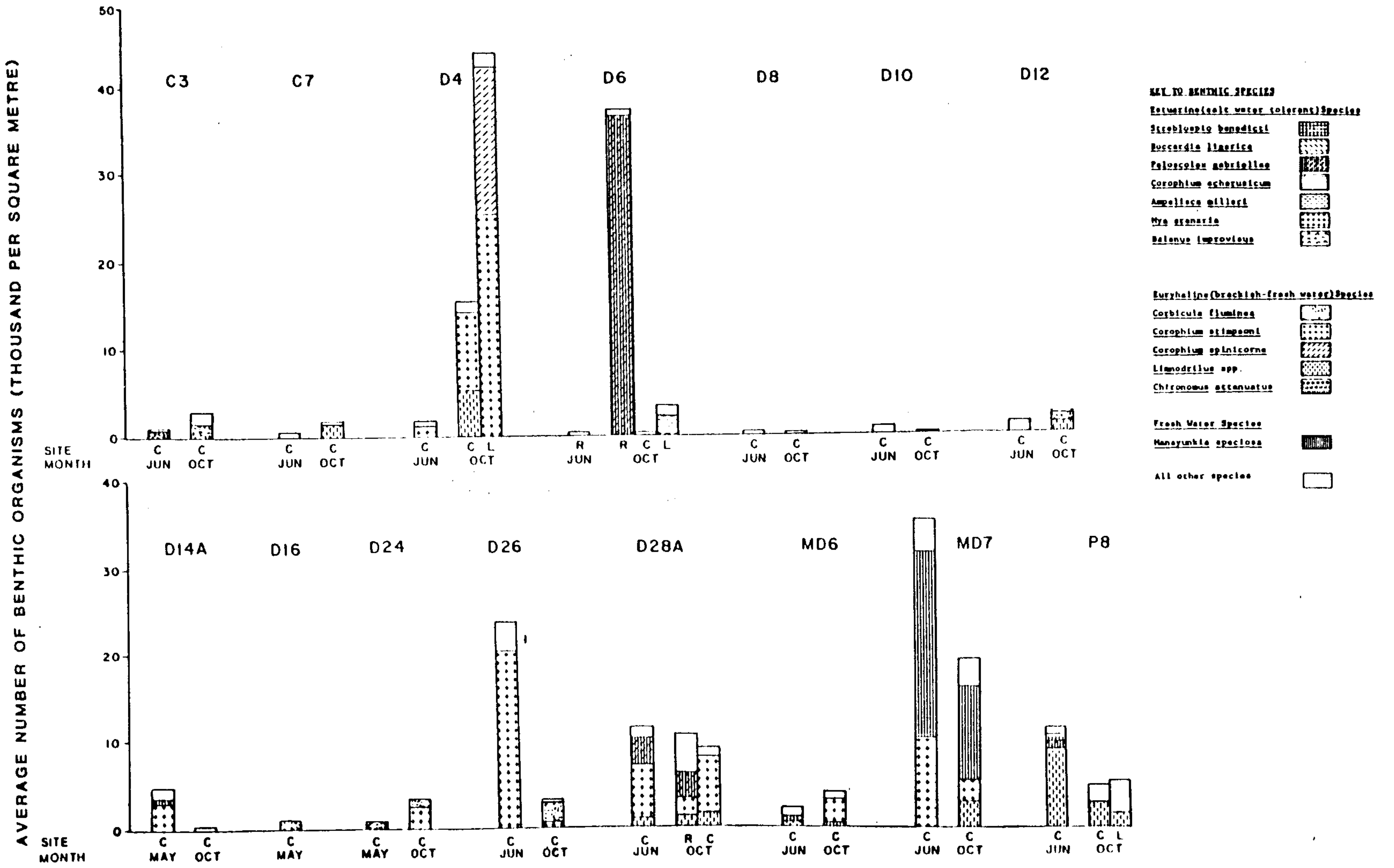
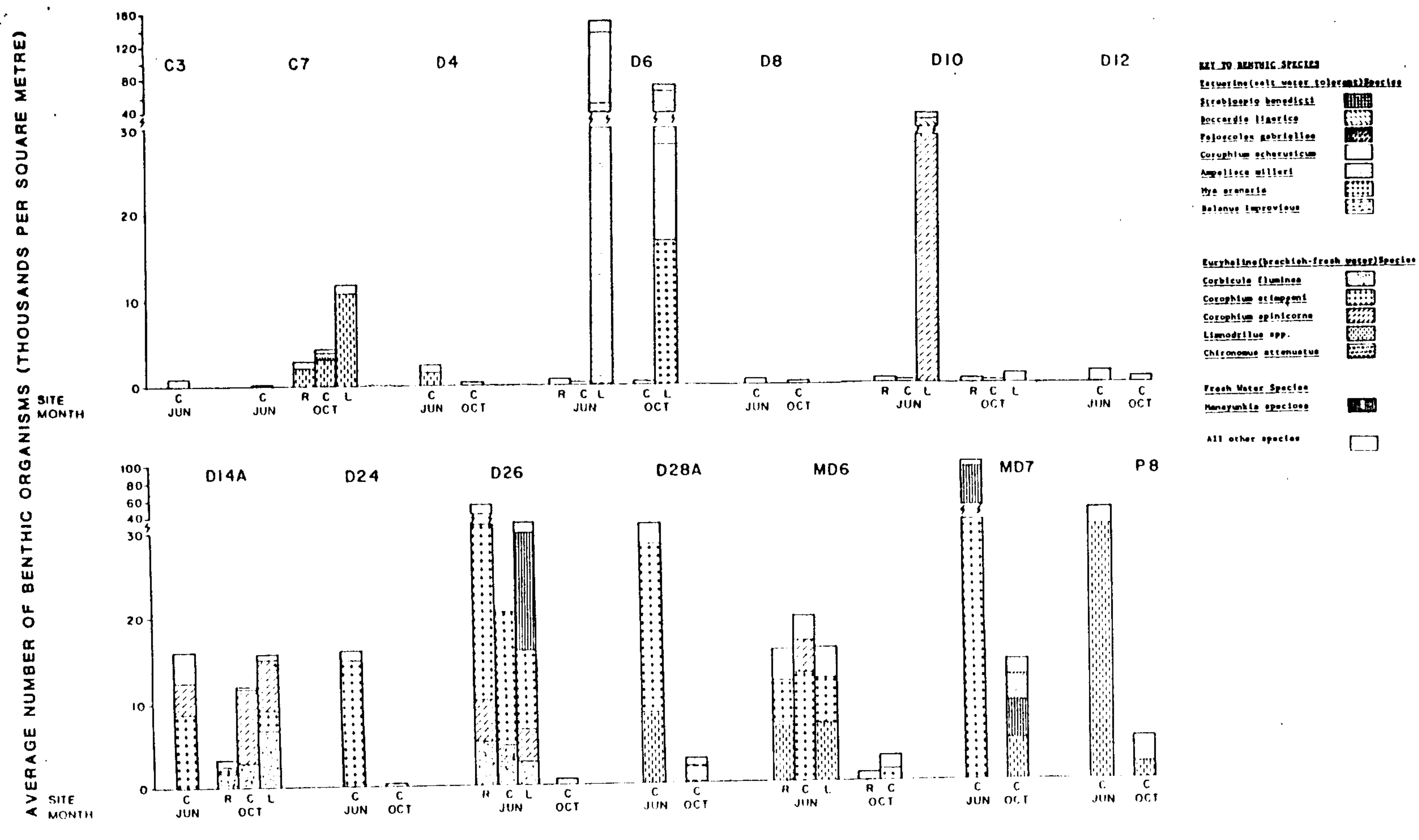


FIGURE 9. 1976 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION



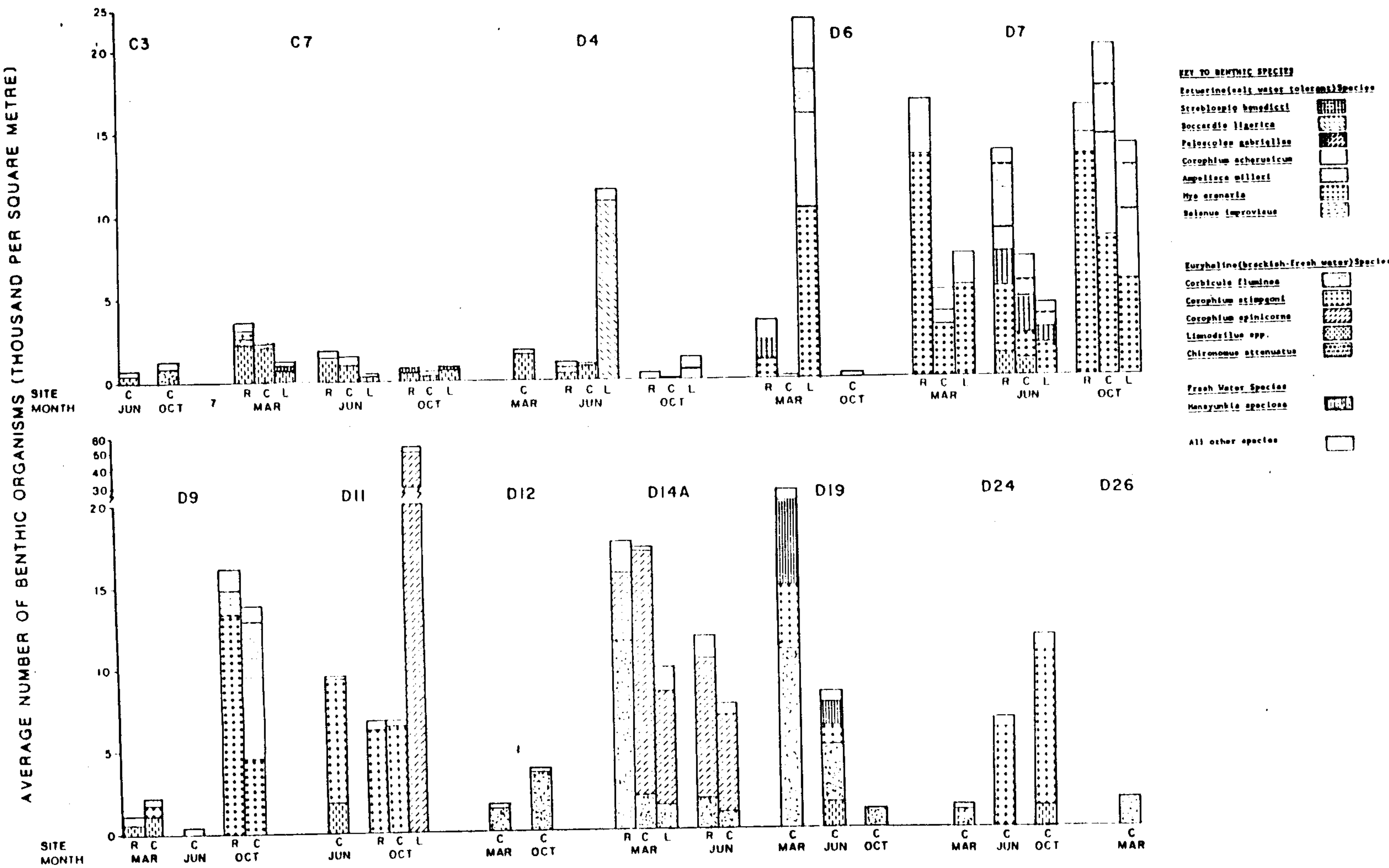


FIGURE 10a. 1977 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION

FIGURE 10b. 1977 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION

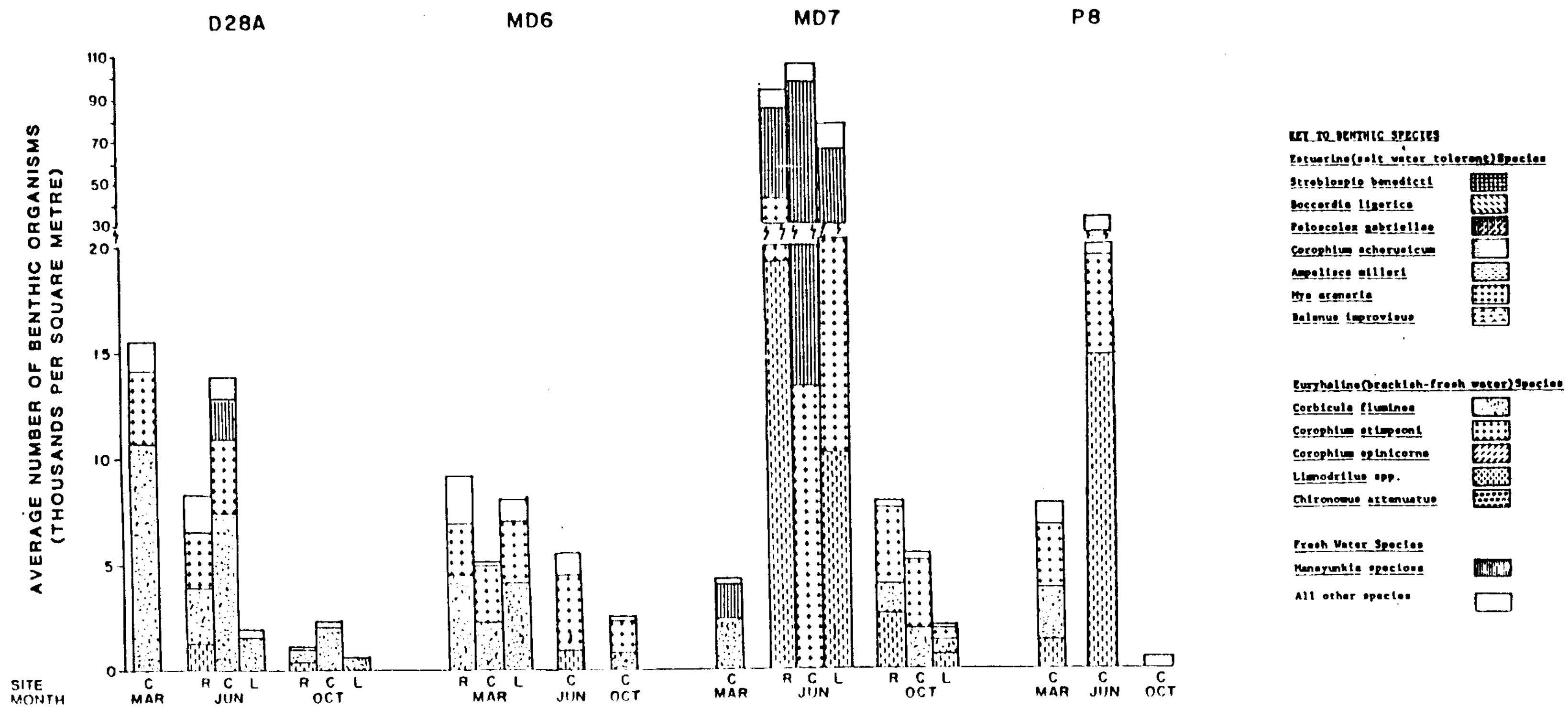


FIGURE 11. 1978 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION

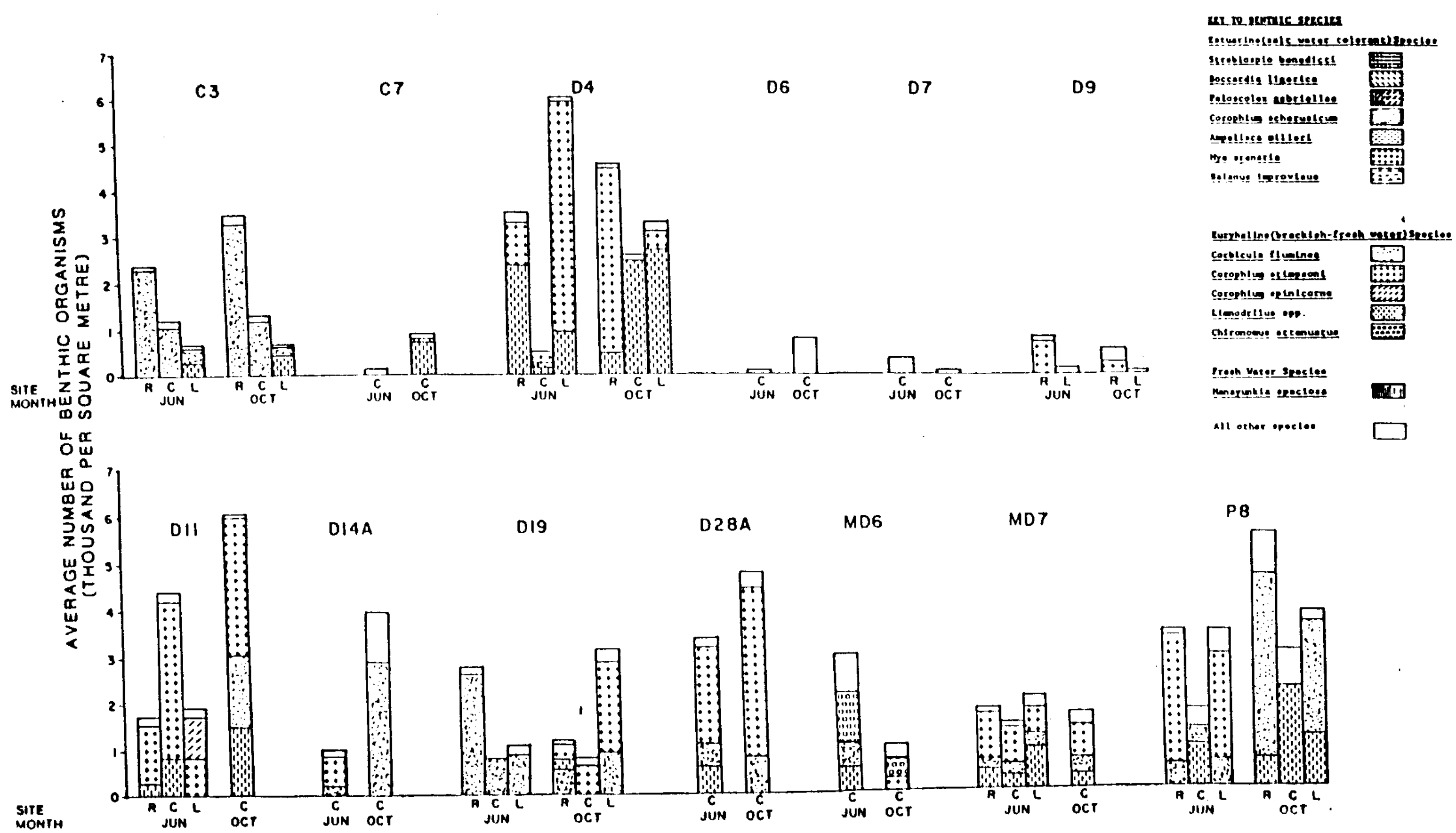


FIGURE 12. 1979 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION

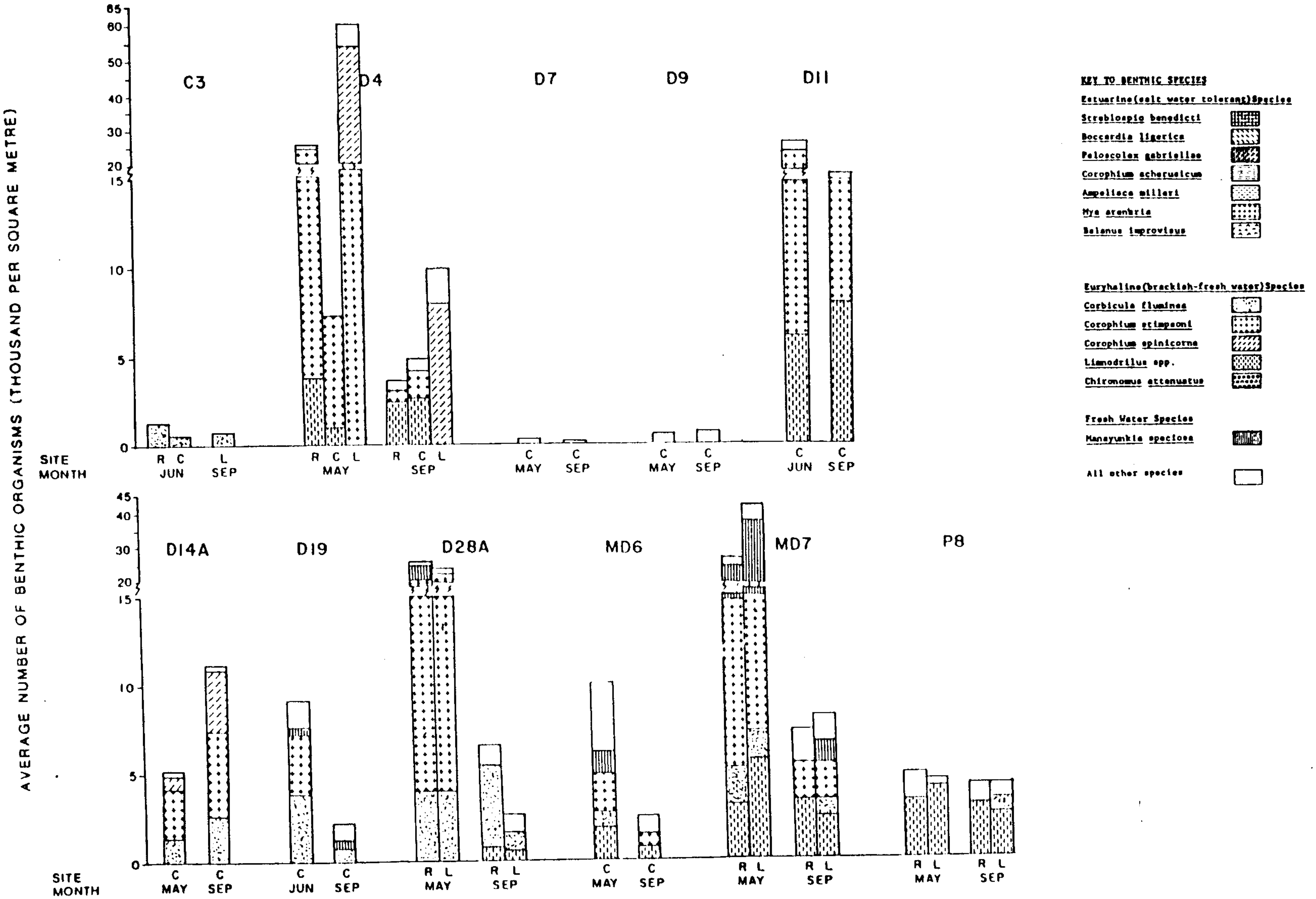


FIGURE 13. 1980 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION

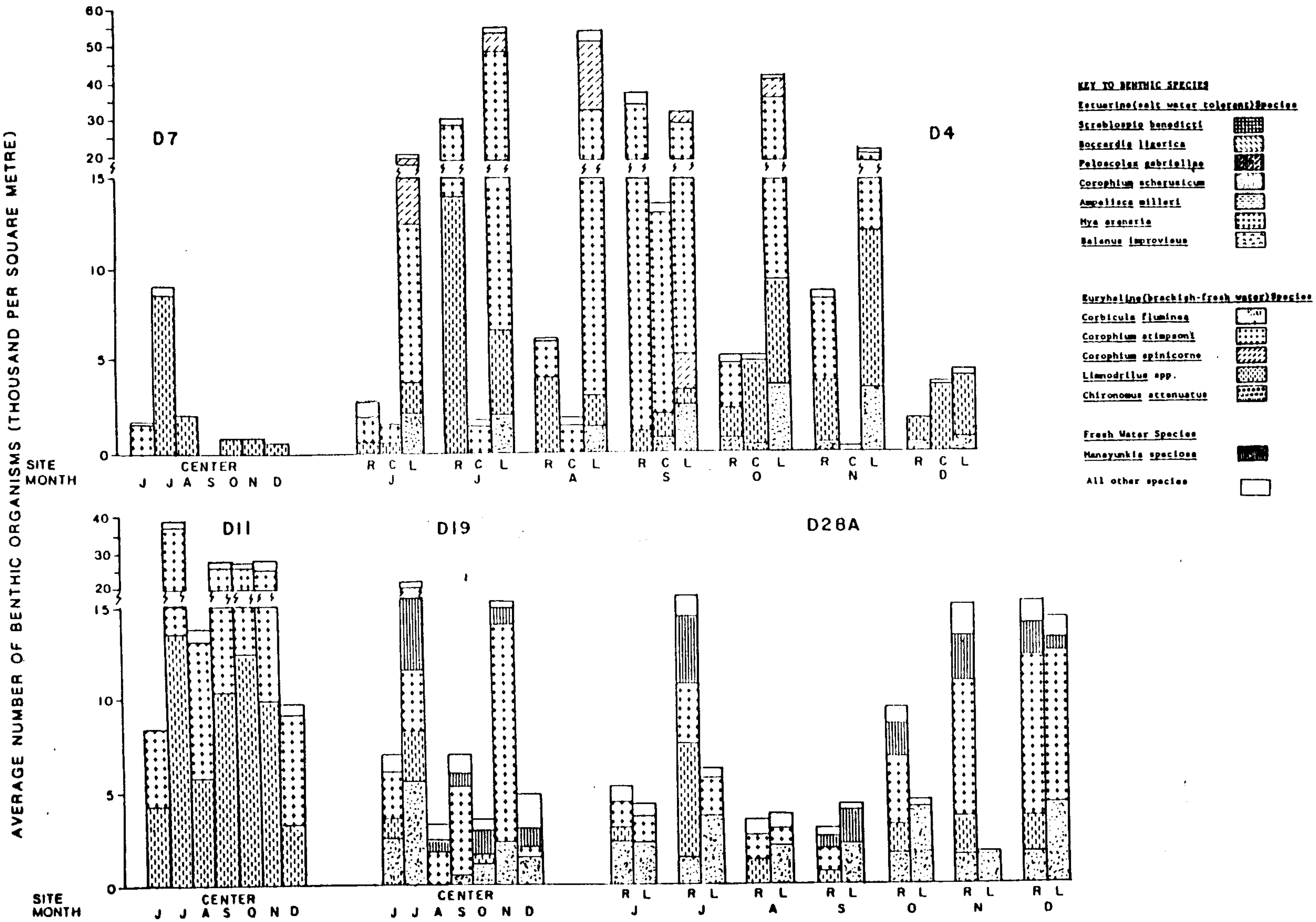
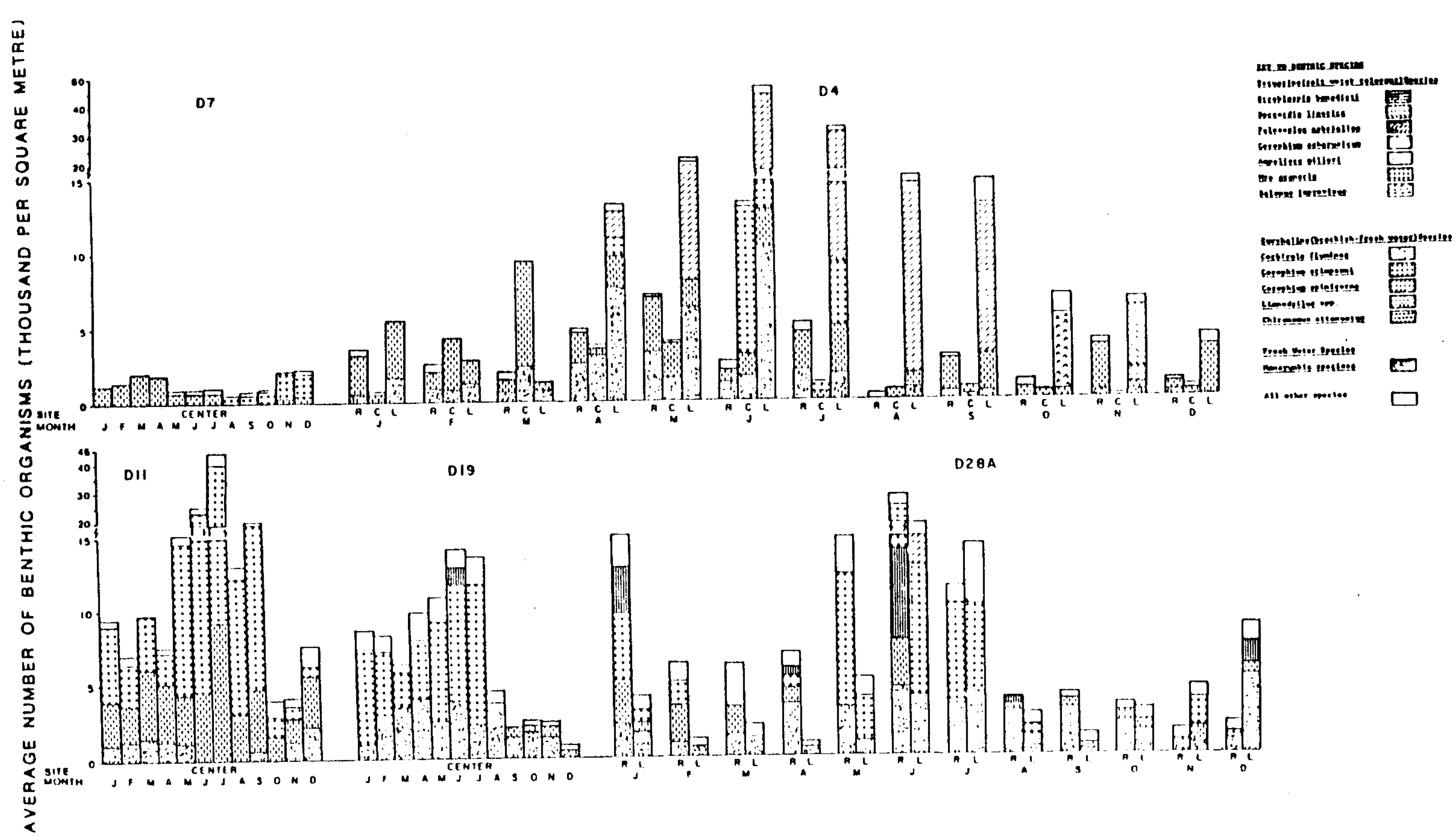


FIGURE 14. 1981 BENTHIC POPULATION DENSITY AND SPECIES COMPOSITION



Semiannual benthos monitoring from 1975 to 1979 has indicated that benthic population densities were greatest in the spring samples. Monthly monitoring beginning in June 1980 confirmed that benthic population increases occur in the spring and early summer. This coincides with the period when water temperatures are 15°C or more. Fifteen degrees appears to be a threshold for the onset of reproduction for benthos in other estuaries as well. Maximum population densities in the Sacramento-San Joaquin estuary were observed from May through November. Seasonal and regional density fluctuations reflected local changes in the abundance of one or more of the dominant taxa. Although the predominant species are practically ubiquitous east of Grizzly Bay, they do exhibit some regional and seasonal differences in abundance and distribution.

The following section summarizes the differences observed as a result of monthly benthic monitoring. These species are also discussed with reference to what is known about their life history traits.

Limnodrilus spp.

Limnodrilus worms are among the dominant organisms in the sampling area. They are highly adaptable to varying environmental conditions, and are tolerant of polluted conditions and low oxygen levels in the sediments (Brinkhurst, 1972). These tube worms can burrow to depths of up to 18 centimeters when exposed to environmental stress.

Worldwide studies of Limnodrilus at many locations indicate that these tubificids do not have a restricted breeding season. Brinkhurst (1972) and Kennedy (1966) reported that L. hoffmeisteri and L. udekemianus, two species collected in the DWR monitoring area, may breed either year-round or seasonally in different environments. Limnodrilus reaches reproductive maturity at 6 months to more than 1 year of age (Kennedy, 1966; Brinkhurst, 1972). Where temperatures remain above 15°C and the substrate is rich in organic material and fines, breeding is continuous. Even in otherwise favorable habitats, breeding ceases when temperatures fall below 15°C.

Seasonal changes in population density of Limnodrilus may or may not correspond closely with reproductive activity. Hatching of immature worms from cocoons may depend on environmental conditions (Kennedy, 1966). Therefore, breeding and hatching may occur at widely spaced intervals. The DWR sampling method only enumerates hatched individuals.

Crumb (1977) observed a relationship between annual temperature cycles and population density of L. hoffmeisteri and L. udekemianus in the Delaware River. Peak densities of the former species were collected from organically rich mud substrate when temperatures were 20-25°C in the spring. Populations of the latter species peaked in the late fall and early winter when temperatures were decreasing.

Tube worms of the genus Limnodrilus have been collected at all stations from Grizzly Bay (D7), where they are the most numerous benthic invertebrate, eastward into the Delta. Densities of 5,000 to 15,000 worms per square meter were observed in 1980 and 1981 at the western Delta stations, Pt. Sacramento (D4) and Sherman Lake (D11). Higher densities were found at station D11. The stable, predominantly silt and clay substrate with moderate organic content, moderate current velocity, and shallow brackish water apparently provide favorable habitat in Sherman Lake, supporting large populations year round. Limnodrilus spp. were found at densities up to 30,000 per square meter in the freshwater reaches of the eastern Delta in the South Fork Mokelumne River below Sycamore Slough (MD7) and in the San Joaquin River at Buckley Cove (P8). These stations were not sampled after

1979, so it is not known if the densities found are typical. Monthly sampling densities of Limnodrilus at two other interior Delta stations, Franks Tract (D19) and Old River opposite Rancho del Rio (D28A), were much lower, usually less than 5,000 per square meter.

The distribution and abundance of Limnodrilus spp. over wide reaches of the upper estuary indicate that they tolerate a relatively broad range of salinities. Since the 1980 monthly sampling program began, the highest densities have been found in brackish water. But these worms also survive the extreme salinity fluctuations of the upper estuary in Grizzly Bay (D7), albeit at much lower densities. Of the relatively limited number of species collected in Grizzly Bay, Limnodrilus was usually the most numerous organism in the benthic samples from this location. Limnodrilus was even able to survive the prolonged salinity increases of the 1976-1977 drought. A few, usually less than 10 individuals per square meter, have been collected far downstream, at Carquinez Strait (D6). Moderate densities were found in the freshwater regions of the Delta as well. The ability of Limnodrilus to burrow and survive in deeper sediments may explain its persistence under a wide range of conditions. In regions where short-term salinity fluctuations and/or anoxic conditions may adversely affect the presence or abundance of other species, Limnodrilus appears to persist. Under more predictable or less stressful conditions in the interior Delta, interspecific competition may be a more important determinant of Limnodrilus abundance.

Corbicula fluminea

Another major benthic species is the introduced freshwater clam, Corbicula fluminea. This filter-feeding species removes small diatoms and organic detritus from the water (Eng, 1975). Recent studies (Cohen et al., 1984) suggest that dense aggregations of Corbicula may filter a significant portion of the phytoplankton from the water column.

In the DWR monitoring program, Corbicula has rarely been collected west of Pt. Sacramento (D4), and never in large numbers. It is a significant component of the benthic fauna from Pt. Sacramento in the lower Sacramento River, through the lower San Joaquin River and interior Delta to Old River opposite Rancho del Rio (D28A). The highest densities of Corbicula were collected at sites with slow to moderate current velocities, moderate to high levels of fines and organic material, and slightly brackish to fresh water. Data from other estuarine systems also indicate this clam's restriction to freshwater habitats (Dresler and Cory, 1980).

Between 1975 and 1981, Corbicula densities ranged from 2,000 to 12,000 per square meter at stations where they were most abundant (D4, D11, D12, D14A, C3, D19, D26, D28A, MD6, MD7, and P8). Eng (1977) observed densities of 10,000 to 20,000 per square meter in the Federal Central Valley Project's Delta-Mendota Canal. Typical densities of 5,000 per square meter were observed in other estuarine systems (Cherry et al., 1980; Cohen et al., 1984).

The general seasonal pattern of abundance observed for this species in the benthos consists of a single peak in late spring or early summer in the western Delta and a biomodal, spring-summer, late fall increase in the interior Delta. This biomodal occurrence is consistent with the pattern observed by Eng (1977) in the Delta-Mendota Canal. This species has exhibited either a unimodal or bimodal annual population increase in other rivers and estuaries as well (Cohen et al., 1984; Dresler and Cory, 1980; Eng, 1977).

Eng (1975, 1977) reported that Corbicula spawn from April through October in the

Sacramento-San Joaquin Delta when temperatures are greater than 16°C. Brooding of larvae was observed from mid-April through May and from mid-August through September in Delta-Mendota Canal populations of Corbicula (Eng, 1977). Immature clams were held in the adult marsupium for about one month (Eng, 1977). Larval clams are released from the marsupium when temperatures rise above 15°C (Crumb, 1977). Once immature clams are released, they settle out within 48 hours and either burrow into the substrate with their foot or attach to a surface with byssal threads (Dresler and Cory, 1980). Other studies of benthos in the western Delta observed peak recruitment to occur in March (Hazel and Kelley, 1966; Siegfried et al., 1978). Department of Water Resources monthly samples indicate that the observed population peaks, probably corresponding to annual recruitment periods, are similar to the spawning seasons reported by Eng.

Immature clams can be transported by turbulent, rapid flows to regions of lower velocity, where they can settle out in large numbers along channel banks (Eng, 1977). Encrustations of the amphipod Corophium may provide a nursery substrate for immature clams (Eng, 1977). Hazel and Kelley (1966) suggested that young clams may be carried downstream in the spring from the interior Delta. During March 1976, Siegfried et al. (1978) collected large numbers of immature Corbicula in the water column and in sediments in the western Delta.

Small juvenile Corbicula, less than 2 millimeters in diameter, were abundant in the DWR spring benthos collections from Pt. Sacramento (D4) in the western Delta. The largest clams, more than 2.5 centimeters in diameter, were typically collected from the interior Delta stations, Franks Tract (D19) and Old River opposite Rancho del Rio (D28A). Clams up to about 2 centimeters in diameter (second year clams according to Eng, 1975) were most common in the western Delta. It is not known whether this represents an actual age difference or merely a regional difference in growth rate.

In the western Delta, it is possible that immature clams settle out in the spring and grow for about 10 months before the next spring's high flows scour the substrate, removing most of the pre-adult clams. Rising salinities late in the year may also contribute to limiting the establishment of large, permanent and reproductively active Corbicula populations in the region. In the interior Delta during fall, when flows are reduced, Corbicula populations sometimes increase. This may be due to the in situ production of larvae, which settle locally instead of being transported downstream.

The data suggest that stable, persistent, adult Corbicula populations in the freshwater portions of the interior Delta may be responsible for recruitment in the western Delta. It appears that tiny juvenile clams are transported downstream by high spring outflows. They settle out in calmer water along channel banks and in flooded tracts and may form dense aggregations where substrate conditions favor colonization. A similar phenomenon was observed by Eng (1977) studying Corbicula in the Delta-Mendota Canal. Rising salinities in the fall followed by scouring current velocities in the winter and early spring may prevent establishment of large, permanent Corbicula populations in the western Delta. Flow reversals that may occur during water export at Delta pumping stations probably contribute to dispersal of this species upstream as well as downstream.

Corophium spp.

Two species of tube building, encrusting amphipods, Corophium stimpsoni and C. spinicorne, were the most abundant organisms in the monitoring samples.

Both are detritivorous filter feeders, collecting small particles for food. Small particles are also used for building their tubes (Barnes, 1974). These species have occasionally been found west of Pt. Sacramento (D4) during periods of unusually high outflows, but they are normally most abundant from D4 in the western Delta through the central Delta. Hazel and Kelley (1966) also observed this species to be most abundant in these areas. Compared to other species of this genus, they are adapted to freshwater environments. For example, C. acherusicum, normally restricted to the more saline waters of San Pablo and San Francisco bays, was able to establish high densities upstream in Suisun and Honker bays (D6, D7, and D9) by the spring of 1977, the second year of the drought.

C. stimpsoni, the most numerous benthic organism collected in DWR samples, often reaches densities of 20,000 to 50,000 per square meter. Its distribution is similar to that of Corbicula, being most abundant at sites with moderate current velocities, moderate levels of fine sediments and organic material, and slightly brackish to fresh water.

Although frequently found at high densities with C. stimpsoni in the western Delta, C. spinicorne is collected in very low numbers in the interior Delta in DWR samples. By contrast, Hazel and Kelley (1966) and Eng (1975) found C. spinicorne to be most abundant in the interior Delta. According to Hazel and Kelley (1966), C. spinicorne appeared to prefer coarse substrate (cobble and levee rocks). These substrates are not sampled by DWR. C. spinicorne reaches extremely high densities on the left bank at Pt. Sacramento (D4). The higher percentage of coarser substrate (49 percent sand) on the left side of the channel may provide more preferred habitat for C. spinicorne, which is never collected in significant numbers on the right bank. C. stimpsoni, however, is found on both sides of the channel. This possible substrate preference might explain the low numbers of C. spinicorne observed in samples from the interior Delta, where sampling stations have substrates higher in clay and silt. The farthest west this species has been repeatedly collected in abundance by DWR is at Big Break (D14A).

Recruitment of these two species of Corophium was apparently responsible for the annual large spring-early summer increase in total benthos standing crop at every station except Grizzly Bay (D7). C. stimpsoni is typically the most numerous of the two species in most samples. A similar pattern is seen in samples collected between 1975 and 1979. In 1980, peak Corophium densities were observed at Pt. Sacramento (D4) and Sherman Lake (D11) from June through November. In 1981, a dry year, C. spinicorne was the major amphipod at D4, while C. stimpsoni predominated at D11 from May through September. This corresponds to the pattern observed in this same region during 1976, the first year of the drought, by Siegfried et al. (1978).

While the highest population densities of both species of Corophium occur at the brackish water stations, C. spinicorne appears to tolerate higher salinities than does C. stimpsoni. During the 1976-1977 drought, C. spinicorne was the predominant amphipod at Chipps Island (D10), Sherman Lake (D11), and Big Break (D14A). During 1981, a dry year, it replaced C. stimpsoni at D4 as the most abundant amphipod. Peak densities of C. stimpsoni occurred somewhat farther upstream at Sherman Lake in 1981, rather than at Pt. Sacramento.

When ECs are above 5,000 uS/cm in the western Delta, higher than usual densities of C. spinicorne were collected, and C. stimpsoni numbers were reduced. Figure 15 shows that in 1981, in the absence of normal high spring outflows, conductivities reached late summer

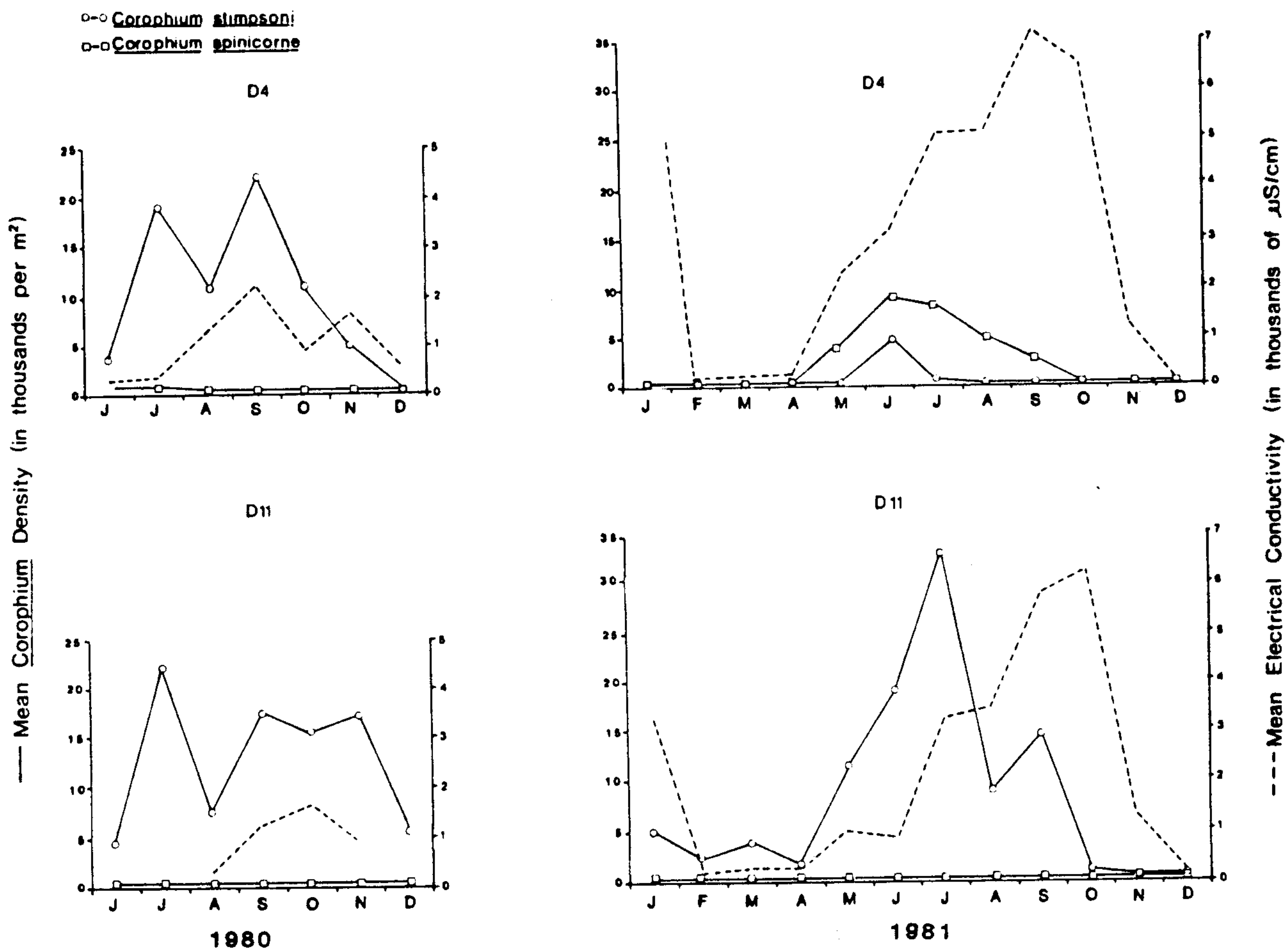


FIGURE 15. CHANGES IN COROPHIUM DENSITY AND DISTRIBUTION ASSOCIATED WITH CHANGES IN ELECTRICAL CONDUCTIVITY IN THE WESTERN DELTA DURING A WET YEAR, 1980, AND A DRY YEAR, 1981

levels by May at D4 and by early July at D11. This may have been the cause of the severe reduction in C. stimpsoni populations at Pt. Sacramento (D4). There was a small density increase during June, but no summer-fall increase as in 1980 at this station. By comparison, C. stimpsoni populations at Sherman Lake (D11) exhibited the more typical pattern of population increase, a July and September peak. Interestingly, the spring population of C. stimpsoni at D11 occurred before EC reached 5,000 uS/cm. Hazel and Kelley (1966) and Siegfried et al. (1978) have indicated that these amphipods appear to be limited by salinity intrusion.

Sherman Lake (D11), more protected from salinity intrusion than Pt. Sacramento (D4), may be a refuge for C. stimpsoni during dry years. Siegfried et al. (1978) suggested that this might account for population shifts observed during the first year of the 1976-1977 drought. Once freshwater outflows increase and EC falls below 5,000 uS/cm, C. stimpsoni probably recolonizes the main channels, either from protected refuges or upstream populations.

At the interior Delta stations, Corophium densities were lower and more variable throughout the year compared to the western sampling sites. C. spinicorne, when collected, was usually less than 10 percent of the total population density. During 1980, C. stimpsoni densities at Franks Tract (D19) and Old River opposite Rancho del Rio (D28A) were highest in November and December, when salinities remained low. In 1981 ECs rose above normal levels at these stations in July. Peak standing crops were observed much earlier in 1981, from May through July. Monitoring results from D19 and D28A in 1976 and 1977 also suggest that in dry years peak population densities occur in the spring, while in wet years (1978) large numbers are also collected in the fall.

Although Corophium spp. are the most numerous benthic invertebrates in the Delta, little information is available on their life history. Corophium have direct development (Barnes, 1974); that is, the young resemble tiny adults. The large numbers of Corophium collected by DWR in the western Delta during the late spring and early summer are primarily tiny young of the year.

Siegfried et al. (1978) reported that at Sherman Lake, two generations of C. stimpsoni were responsible for an annual June through August population peak. Density increases starting in March and peaking in June were attributed to reproduction by amphipods born the previous summer. Those Corophium born in early spring were believed to mature rapidly and reproduce by late summer. This second cohort supplied the overwintering generation. The late spring and summer blooms observed during monthly monitoring by DWR may correspond to this dual generation production. Unusually high salinities in the early summer may inhibit maturation and reproduction by the overwintering cohort. Production of an overwintering generation might be reduced, affecting population densities in the following year.

Currents may also play an important role in dispersal and colonization of Corophium in the estuary. Unusually large numbers of Corophium have been collected at Grizzly Bay (D7) during high spring outflows in 1980 and 1982 (preliminary results). Siegfried et al. (1978) report that C. stimpsoni migrate into the water column at night, and this probably aids dispersal. The greatest concentrations of both adult and immature Corophium are consistently collected in the western Delta, in the vicinity of the highly productive entrapment zone (Arthur and Ball, 1977; Arthur and Ball, 1980; California Department of Fish and Game et al., 1974). While resident populations may be responsible for the major spring and early summer blooms in this region, spring flows may be an important source of colonists from upstream populations unaffected by saline intrusion.

Manayunkia speciosa

Manayunkia speciosa, a tube building, colonial polychaete worm, is the fourth most numerous benthic invertebrate collected by DWR. Although reported to be euryhaline (Croskery, 1978), it has rarely been collected west of Franks Tract (D19). Poe and Stefan (1974) report it to be a freshwater species. It has been collected in the interior Delta at densities of from 2,000 to 50,000 per square meter. Between 1975 and 1979, the greatest populations of M. speciosa were found in South Fork Mokelumne River (MD7), San Joaquin River (D19, D26), and Old River (D28A). Since 1980, densities of between 2,000 to 10,000 per square meter were collected frequently at D19 and at the right bank of D28A.

Hazel and Kelley (1966) first reported the presence of this worm on the West Coast from the San Joaquin River and one locality in Oregon. It appears to be limited to freshwater habitats with slow to moderate current velocities and substrates containing fine particles, with which it constructs its tube (Poe and Stefan 1974).

The hermaphroditic M. speciosa reproduces sexually or asexually within its tube. The young mature within the parental tube (Croskery, 1978). The tube is constructed of fine particles cemented together by a mucoid secretion (Poe and Stefan, 1974). Small adult worms crawl out of the parental tube after hatching and form their own tube nearby (Croskery, 1978).

This worm's pattern of distribution and abundance indicates that it probably cannot tolerate EC above 500 uS/cm for prolonged periods. Mokelumne River EC is typically below 200 uS/cm. Areas with slow to moderate currents and substrates rich in organic material support the densest populations of M. speciosa. Its breeding season is apparently restricted to spring. Of all the common benthos, this worm is probably the least tolerant of rapid currents and elevated salinities. Populations probably expand relatively slowly through the growth of localized colonies. High flows, which could remove the fine sediments or carry worms to the brackish regions of the Delta, would not be favorable to this species.

Monthly benthos and substrate sampling since 1980 has led to a better understanding of the relationship between changes in salinity, outflow, and substrate and fluctuations in the benthic fauna.

Salinity

Salinity is a primary factor influencing benthic communities. Average population densities are normally greatest at the brackish water stations of the western Delta. Here, a few species of euryhaline benthos numerically dominate the fauna for much of the year.

Seasonal fluctuations in salinity and outflow regime appear to have the most impact upon species composition and population density in the western Delta. The few species that can tolerate the annual range of salinities are able to reach very high densities. The absence of more stenohaline competitors and the abundance of food resources in the entrapment zone probably contribute to the production of large numbers of a few euryhaline species.

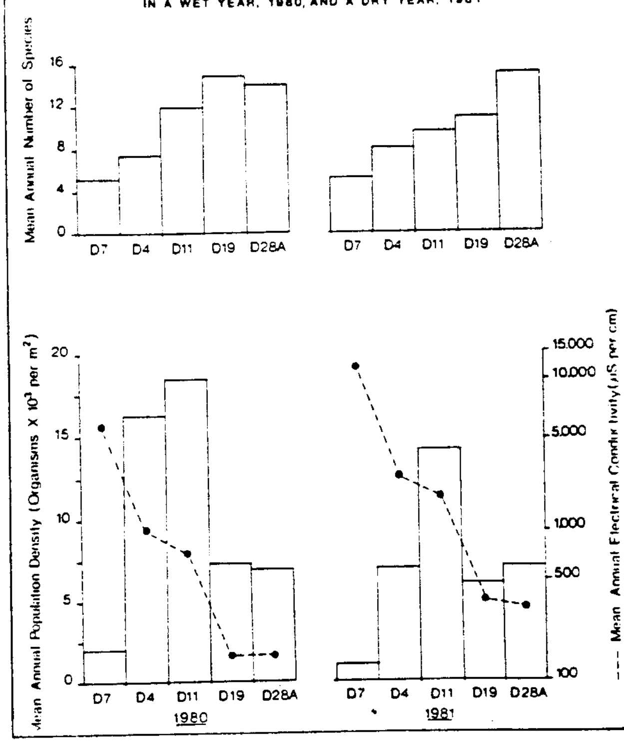
Downstream through Suisun Bay, tidally driven, short-term salinity fluctuations probably prevent establishment of dense benthos aggregations. Only a few species normally occur, and at low densities, in this highly variable environment. Occasionally, other species can temporarily colonize this area. For example, during low outflow years when salinity remains high for many months, saltwater adapted species become established.

In the interior, freshwater reaches of the Delta, population densities were intermediate, but species diversity was much greater than in the western Delta.

Although the species predominating in the brackish zone of the western Delta were also collected in the interior, a greater variety of benthos more specialized for existence under stable, freshwater conditions were found here (see Appendix A). Inter- and intra-specific competition may also contribute to the lower observed population densities in the interior Delta. The general pattern when comparing the average annual salinity, species number, and population density is summarized in Figure 16.

The amount of fresh water flowing through and out of the Delta is the major determinant of the annual salinity regime. During low outflow years, saline waters intrude farther upstream, and higher than normal salinities persist for many more months than usual.

FIGURE 16. COMPARISON OF REGIONAL PATTERNS OF BENTHIC SPECIES NUMBER AND POPULATION DENSITY ASSOCIATED WITH CHANGES IN ELECTRICAL CONDUCTIVITY IN A WET YEAR, 1980, AND A DRY YEAR, 1981

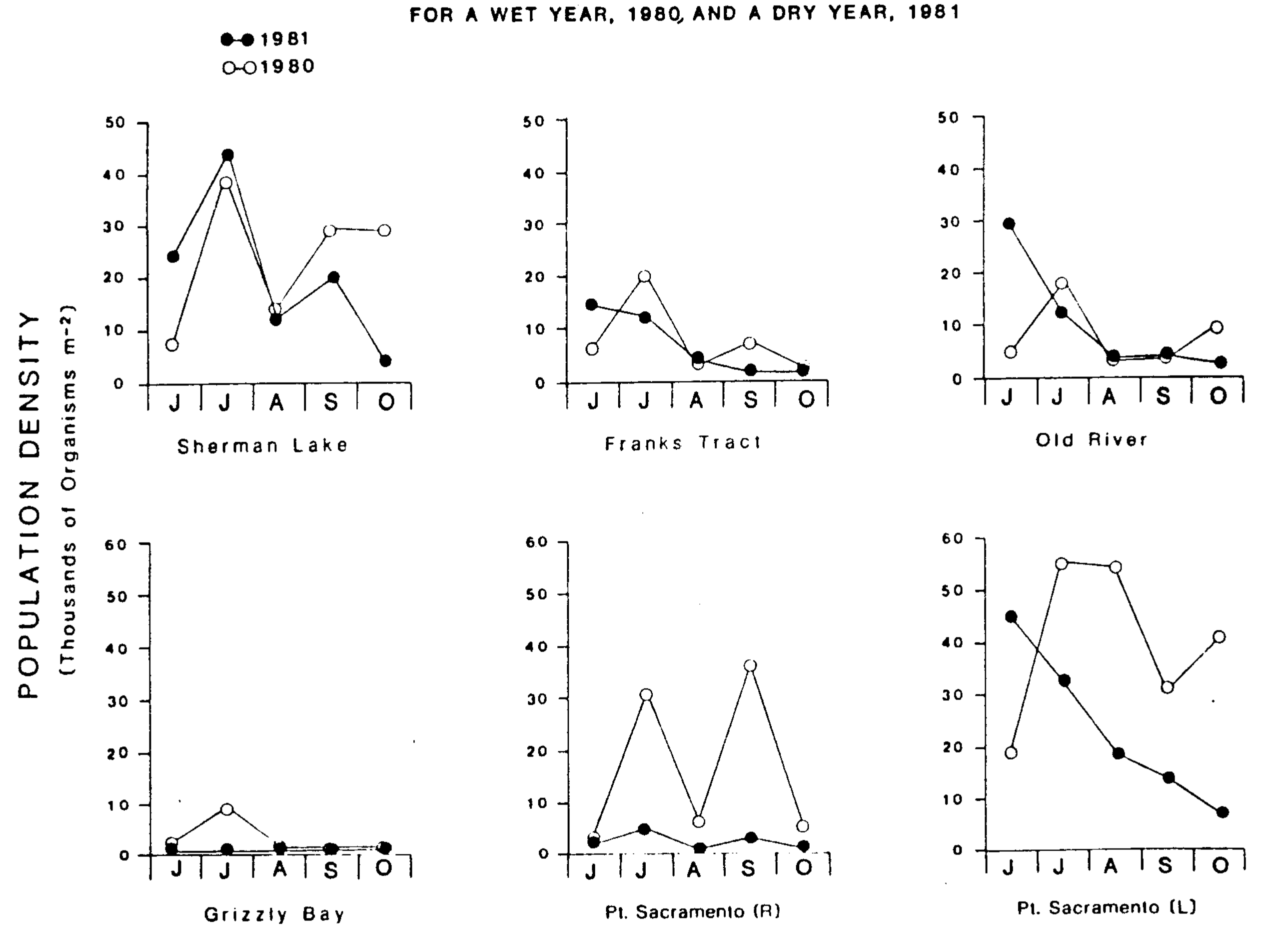


The impact of drought on the benthic community was revealed by the DWR monitoring program during 1976 and 1977. Portions of the western Delta that normally support the largest numbers of benthos had severely depleted populations. In addition, by 1977, huge numbers of saltwater-tolerant species, typical of San Pablo Bay fauna, were able to colonize the Suisun Bay area.

A similar, though less extreme, dry period occurred in 1981. Figure 16 shows that at the most westerly stations, Grizzly Bay (D7), Pt. Sacramento (D4), and Sherman Island (D11), a large average annual increase in EC (dashed line) in 1981 corresponded to a large decrease in average annual population density (histogram). Monthly sampling enabled DWR to examine the relationship of these conditions to benthic populations through time and to compare 1981, a dry year, to 1980, a wet year. The most westerly stations bore the brunt of salinity intrusion during 1981.

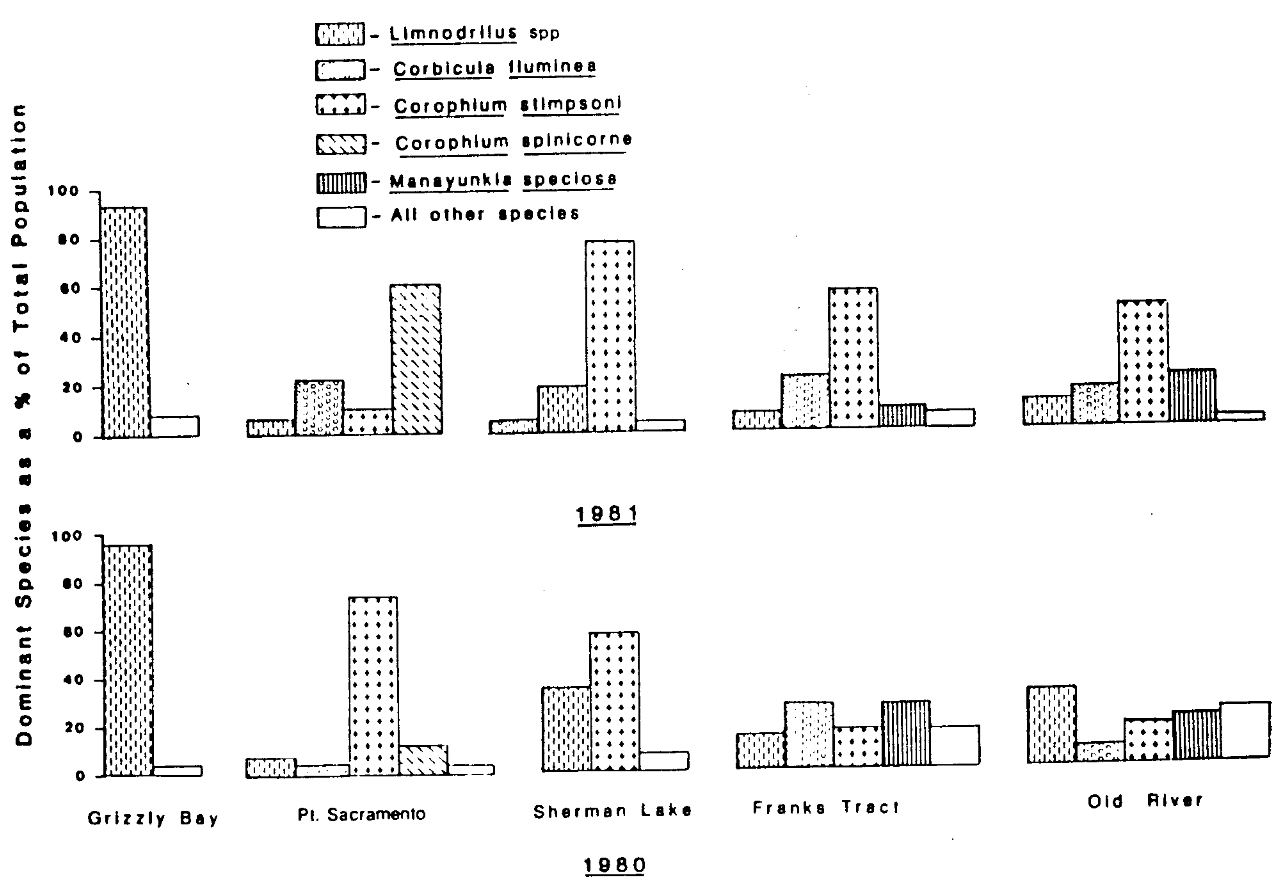
Figure 17 compares average population densities during the months when benthos normally undergo annual population increases. In 1981, total population density was unusually low at Pt. Sacramento (D4). The secondary fall bloom observed at all stations except Grizzly Bay (D7) during 1980 was significantly reduced or eliminated in 1981.

FIGURE 17. COMPARISON OF BENTHIC POPULATION DENSITIES DURING THE ANNUAL RECRUITMENT PERIOD FOR A WET YEAR, 1980, AND A DRY YEAR, 1981



In addition to the reduction in numbers of the dominant benthic taxa, relative abundance and distribution patterns shifted in 1981 (see Figure 18). As in 1977, more saltwater-tolerant species temporarily appeared in Suisun Bay and the western Delta (Figure 14). Among these were significant numbers of Boccardia ligerica, Mya arenaria, and Balanus improvisus. The numbers of Limnodrilus spp. decreased, particularly at station D11, where they had been most abundant in 1980. Corophium spinicorne replaced C. stimpsoni as the dominant amphipod at Pt. Sacramento (D4). This also occurred during the drought (Figures 9, 10, and 14). The region of highest C. stimpsoni population density shifted eastward toward the less saline stations (Figures 14 and 15). The numbers of Manyunkia speciosa, the freshwater polychaete, declined (Figures 13 and 14). Many other freshwater species normally common at Franks Tract (D19) and Old River opposite Rancho del Rio (D28A) disappeared or were less numerous in 1981, compared to 1980. The "all other species" category in Figure 18 shows a reduction in overall abundance of the many species that normally occur at D19 and D28A in low densities (less than 10 percent of the total population). In 1981 this was primarily due to the absence of a number of annelid and arthropod species. Corbicula, unexpectedly, did not appear to be adversely affected. In fact, its range and population densities increased in 1981.

FIGURE 18. CHANGE IN DISTRIBUTION PATTERN AND RELATIVE ABUNDANCE OF THE DOMINANT BENTHOS BETWEEN A WET YEAR, 1980, AND A DRY YEAR, 1981



Monitoring benthos populations has shown that changes in density and distribution of dominant species may be an indicator of major water quality changes. The critical salinity threshold for dominant benthic species in the western Delta appears to occur at ECs of around 5,000 uS/cm. When EC rises to this level in June and remains at or above this level, total population density is reduced and many species appear to be concentrated in areas with relatively lower EC. Specific studies of this hypothesis would be valuable.

The effects of elevated salinity on benthos populations appear to be temporary. Preliminary examination of monitoring results from 1982 (a wet year) indicates that high population densities and range expansions among many benthic species were associated with the return of high freshwater outflows and decreased EC.

The 1976-1977 drought ended with extremely high Delta outflows of 60,000 to 170,000 cubic feet per second from January through May 1978. Although 1978 was a wet year, the numbers of benthos collected in both spring and fall were the lowest since monitoring began in 1975 (see Figure 11). Several factors may have contributed to this continued, temporary decline after cessation of the drought.

Cumulative effects of two consecutive drought years may have severely depleted adult benthic stocks. In addition to the adverse impact of high salinities, low flows might have limited dispersal and reduced the transport of detrital nutrient supplies. Spring outflows in 1978 were unusually high. Spring is the normal reproductive season, when young are produced and dispersed throughout the system by the currents, but observed benthic population densities were unusually low during 1978. High spring flows may have washed out established populations, scoured the substrate, and prevented settlement and colonization by immatures as well as adults. By 1979, benthic populations appeared to have recovered to more typical densities and species composition (see Figure 12).

The dry year of 1981 was also followed by high spring outflows, but of a lower magnitude than in 1978. Preliminary examination of 1982 monitoring data suggests that these flows did not adversely affect the benthic fauna. Below some as yet undetermined threshold limit, high spring outflows may benefit the major taxa by dispersing adults and immatures and providing a rich flux of phytoplankton and other organic food particles to the relatively sessile benthic community.

Substrate Composition and Current Velocity

Monitoring benthos and substrate also suggests a possible relationship between current velocity, substrate composition, and benthos density and distribution. Table 4 summarizes the average substrate composition and compares it with average benthic population density and species number at selected sites from Grizzly Bay (D7) upstream into the central and southern Delta to the San Joaquin River at Mossdale Bridge (C7). Slow to moderate current velocities provide a mixture of small particulate material (sand, silt, clay, and organic detritus) used by many species of benthic invertebrates for food and shelter. In general, locations with this type of current regime support larger, more diverse benthic communities.

Grizzly Bay (D7), in the upper estuary, has very stable, high levels of constant fine sediments and highly variable salinities. Salinity is probably the major environmental factor controlling benthic species distribution and abundance at this site. Few species can tolerate the extreme short-term salinity fluctuations. The benthic fauna was primarily tube worms (_Limnodrilus_ spp.). These are adapted to conditions of life in the mud sediments, with low oxygen

Table 4

COMPARISON OF SUBSTRATE COMPOSITION AND
BENTHIC POPULATION DENSITY AND NUMBERS OF SPECIES AT
SELECTED STATIONS 1975-1981*

Station (Site)	Substrate Percent Sand	Percent Fines	Percent Organic	Average Annual Population Density (# m-2)	Average Annual Number of Species
Suisun Bay					
Grizzly Bay (D7)	5	95	8	2,800	7
Western Delta					
Sherman Lake (D11)	32	68	8	15,200	9
Big Break near Oakley (D14A)	18	82	14	7,800	8
Pt. Sacramento (D4R)	54	46	5	7,300	8
(D4C)	77	23	3	3,600	6
(D4L)	57	43	21	22,000	11
Interior Delta					
Franks Tract (D19)	12	88	12	7,200	10
Sacramento River near Rio Vista Bridge (D24C)	87	13	2	5,700	8
South Fork Mokelumne River below Sycamore Slough (MD7R)	18	82	8	27,000	11
(MD7C)	4	96	8	32,000	11
(MD7L)	3	97	10	13,500	12
San Joaquin River at Potato Point (D26C)	62	38	3	8,800	8
San Joaquin River at Buckley Cove (P8C)	28	72	5	11,000	12
Export Channels					
Old River opposite Rancho del Rio (D28AR)	39	61	10	10,000	17
(D28AL)	59	41	7	6,400	10
San Joaquin River at Mossdale Bridge (C7C)	89	11	2	1,400	7

*Average values may differ from those based only on 1980-1981 data.

levels and organic material incorporated deep in the substrate. These worms are able to burrow through the mud as much as 18 centimeters to temporarily escape the most adverse conditions at the surface layers and extract organic material incorporated in the deeper sediments for food (Brinkhurst, 1972; Crumb, 1977). Some benthic species collected at this site are motile and can move to a region with favorable conditions; for example, the nereid worm Neanthes succinea. Some organisms, such as the clam Mya arenaria and amphipod Corophium ascherusicum, appeared temporarily in the samples after salinity had remained high for several months at a time.

Within the productive, brackish water environment, the largest populations of benthos were found at the left bank at Pt. Sacramento and Sherman Lake (D4L and D11). The most abundant group was Corophium spp., which may prefer the coarser substrates in this area. The substrate on channel banks at D4 is composed of a mixture of about 60 percent silt and clay and 40 percent sand. The organic content of the substrate is about 10 percent. The amount of organic material in the substrate appears to be generally associated with higher benthic population densities. The right bank at Pt. Sacramento (D4R) appears to have a favorable substrate regime, although it is somewhat variable through time compared to the left bank (see Tables 3 and 4). This side of the channel may be exposed to a wider range of fluctuating current velocities that prevent the establishment and growth of large aggregations of diverse benthos populations. The center channel site at Pt. Sacramento (D4C) is heavily scoured by rapid flows. The substrate is always predominantly sand and usually supports only a few benthic organisms, such as Corbicula and Limnodrilus spp., capable of burrowing into or anchoring themselves to the substrate. Sherman Lake (D11) supported numerous surface encrusting Corophium as well as burrowing Limnodrilus spp.

On the average, the left bank at Pt. Sacramento (D4L) supports higher benthic densities than does Sherman Lake (D11). The major difference appears to be the higher organic content of the sediments at D4L. It appears that stations in the western portion of the Delta (D4, D11, D14A) with relatively greater amounts of fines in the sediments have higher population densities (see Table 4).

In the interior freshwater portions of the monitoring area, benthos density variations were also associated with differences in the substrate regime. The sediment composition evidenced by the higher percentage of fines (more than 80 percent) in the substrate indicates that these stations have the slowest velocities (Tables 3 and 4). Most of the interior Delta stations have high to moderate population densities with relatively more species compared to western Delta stations. Again, the exceptions are those stations (D24C and C7C) with predominantly sandy substrate (see Table 4).

Old River (D28A), a natural channel used to carry water to the State and Federal pumping plants, has relatively faster flows. Based on substrate composition, the channel banks appeared to have dissimilar velocities. The right bank was typically composed of over 70 percent fines, with about 30 percent sand. The left bank was over 60 percent sand. On the average, the left bank supported fewer benthic organisms. Conditions on the right bank at Old River (D28AR) generally support somewhat larger benthic populations than those found in Franks Tract (D19). Substrate composition at D28AR indicates that current velocities are intermediate between those at D19 and D28AL (Table 3). These data suggest that rapid flows may remove finer sediments on the left bank and depress benthic population densities, compared to the right bank.

Another location subject to elevated flows during water export is San Joaquin River at Mossdale Bridge (C7). This station was monitored from 1975 through 1978 (see Figures 8 through 11). Benthic population densities were relatively low, averaging less than 5,000 organisms per square meter. The substrate was predominantly sand and the dominant species was Limnodrilus hoffmeisteri. The average number of species collected at C7 was about five, which is low compared to other interior Delta stations.

Chapter 4. IMPORTANCE OF BENTHOS IN THE FOOD WEB

Benthic invertebrates are present at high densities in the Sacramento-San Joaquin Delta. Their role as a food source for the higher trophic levels in Delta food chains, however, is not well understood. Their detritivorous and phytoplanktivorous habits may also be a significant factor in the recycling of nutrients from the sediments and water column. The following section reviews and discusses what is known from other studies about benthos in the food web.

Benthos as Food

There is relatively little information about the role of benthic invertebrates in the food web of the Sacramento-San Joaquin Delta and estuary. This is probably due in part to the lack of long-term, quantitative studies.

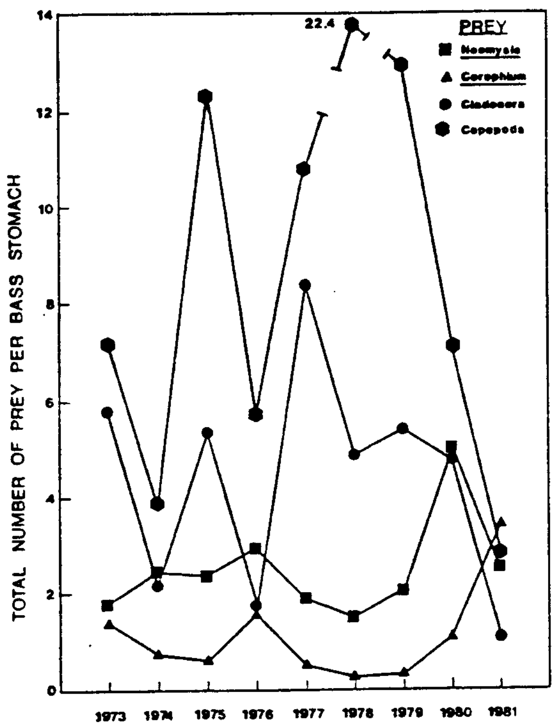
The primary reference on consumption of benthos by Delta fish is the Department of Fish and Game study by Hazel and Kelley (1966). Since then, most dietary studies have concentrated on food habits of juvenile striped bass, *Morone saxatilis*. Recently, gut contents of fish in Suisun Marsh have been examined (Brown et al., 1981; Moyle et al., 1981). The diets of two estuarine shrimp, *Palaemon macrodactylus* and *Crangon franciscorum*, have also been studied (Siegfried et al., 1978; Sitts and Knight, 1979). Carlton (1979) reported the species of introduced benthos found in bird stomachs from San Francisco Bay.

Many benthic species are soft-bodied (e.g. worms) and are digested so rapidly that they would be easily missed in gut analysis (Siegfried, 1980), especially if specimen retrieval is delayed for even a few hours. In addition, numerous benthic species live in tubes or burrows within the substrate, making them less vulnerable to predation (Virnstein, 1979). Those benthos that live on or near the surface (e.g. *Corophium*, *Corbicula*, or aquatic insect larvae such as Chironomidae) or species that have planktonic life stages (e.g. mollusc and arthropod larvae) tend to be the species most frequently encountered in diet studies (Virnstein, 1979). Probably only a few benthic species in the Sacramento-San Joaquin system occur at high enough densities or in large enough accessible colonies to make them of interest as a regular food source to aquatic predators. The most abundant taxa, the amphipods *Corophium* spp. and the clam *Corbicula fluminea*, excluding the soft-bodied, burrowing oligochaetes, are the groups most often identified in fish gut analyses.

Corophium spp. in the western and interior Delta are the benthic invertebrates apparently consumed most frequently by Delta and estuarine fish. Various species of catfish eat *Corophium* (Turner, 1966). Young green sturgeon and white sturgeon (*Acipenser transmontanus* and *A. medirostris*), young chinook salmon (*Onchorhynchus tshawytscha*), centrarchids (sunfish), tule perch (*Hysterocarpus traski*), and threadfin shad (*Dorosoma petenense*) prey heavily on *Corophium* (Radtke, 1966; Sasaki, 1966; and Turner, 1966). Other euryhaline and estuarine fish, such as sculpin, stickleback, yellowfin goby, and starry flounder, also eat these amphipods (Brown et al., 1981).

Corophium can be an important item in the diet of juvenile striped bass. Figure 19 illustrates the frequency of *Corophium* occurrence in striped bass stomachs, compared to the other major prey groups, from 1973 to 1981 (L. Miller, DFG pers. comm).

FIGURE 19. FREQUENCY OF PRIMARY INVERTEBRATE PREY IN THE DIETS OF YOUNG STRIPED BASS (> 25 MM TO < 50 MM) THROUGHOUT THE DELTA AND ESTUARY, 1973-1981



(DATA COURTESY OF L. MILLER, DEPARTMENT OF FISH AND GAME)

As can be seen in Figure 19, peaks in Corophium abundance in bass stomachs coincided with decreases in the consumption of other prey (1976 and 1981). Fluctuations in the consumption of Corophium may be due to many factors such as:

- Prey availability may change due to inherent population cycling.
- Young bass may be feeding in different geographic regions in different years, and prey densities may vary regionally as well.
- Prey food value and predator food preferences coupled with prey availability may affect prey selection.
- Some environmental factor may affect both prey and predator numbers and behavior.
- Population density variations in populations of a competing predator may effect Corophium availability.
- Some combination of the above.

Young striped bass exhibit differential consumption of Corophium according to size and geographic region (see Figure 20). In all regions the frequency of Corophium consumption increased with size of bass. This is not surprising, since Corophium is one of the relatively larger prey organisms (adult length is about 10 millimeters). The observed number of Corophium per stomach is greatest for young fish larger than 50 millimeters. Only in Region VII, in the northeastern Delta, do bass less than 50 millimeters prey to a great extent on Corophium. The area of peak consumption of these amphipods does not strictly correspond to the region of highest prey population density. The most abundant concentrations of Corophium occur in the western Delta near the confluence of the Sacramento and San Joaquin rivers (Regions III, IV, V, and VI in Figure 21) (Hazel and Kelley, 1966; Siegfried et al., 1978).

Most Corophium are apparently consumed by bass larger than 50 millimeters from the vicinity of Antioch upstream into the interior Delta, excluding the upper Sacramento River (Regions V, VI, VII, and VIII) where other prey species densities are lower. This could occur because the preferred prey, Neomysis, is not available in high concentrations except in Suisun Bay. The smaller bass may be feeding in the downstream entrapment some, while Corophium may be a significant food source to larger juvenile bass overwintering in the interior Delta (Moyle, 1976; PGandE, 1981).

Although Corophium are mostly eaten by fish, they are a component in the diet of other organisms in the estuarine food web as well (see Figure 21). They are eaten by the bay shrimp, Crangon franciscorum, and the Oriental shrimp,

Figure 20

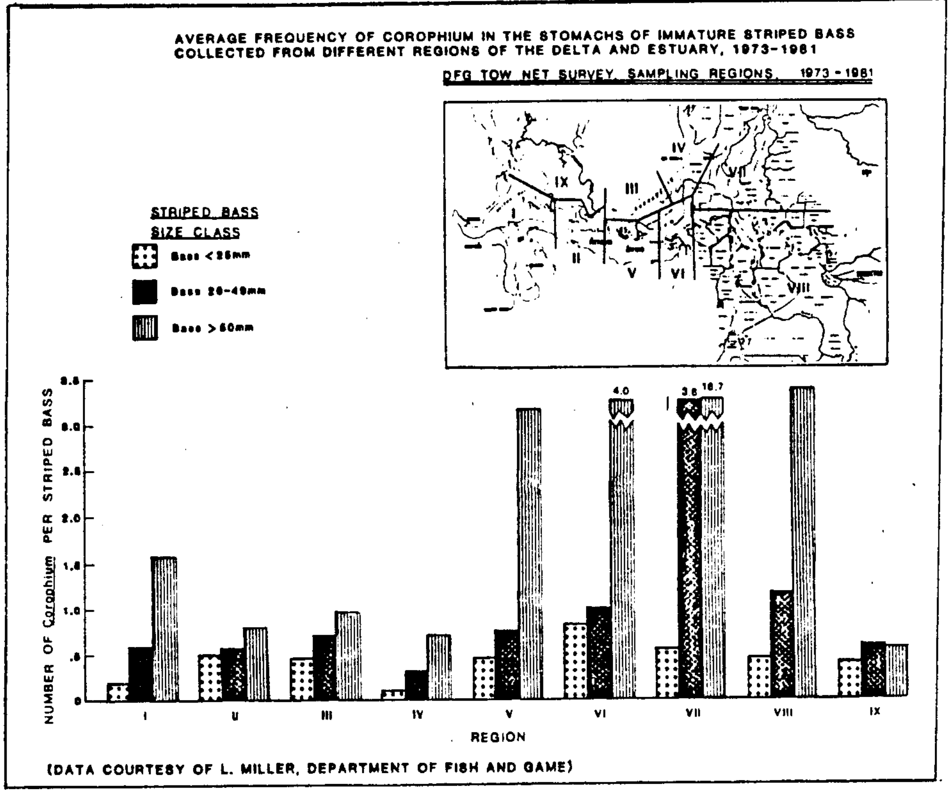


Figure 21

Consumer Species

Benthic Prey Organism	◆ Bay shrimp *Crangon franciscorum*	Oriental shrimp *Palaemon macrodactylus*	▲ White sturgeon *Acipenser transmontanus*	▲ Green sturgeon *Acipenser medirostris*	Threadfin shad *Dorosoma petenense*	▲ American shad *Alosa sapidissima*	◆▲ King salmon *Oncorhynchus tshawytscha*	Delta smelt *Hypomesus transpacificus*	Sacto squawfish *Ptychocheilus grandis*	▲ Black bullhead *Ictalurus melas*	▲ Brown bullhead *Ictalurus nebulosus*	▲ White catfish *Ictalurus catus*	▲ Channel catfish *Ictalurus punctatus*	▲ Striped bass *Morone saxatilis*	Sacramento perch *Archoplites interruptus*	▲ Bluegill *Lepomis macrochirus*	▲ Green sunfish *Lepomis cyanellus*	▲ Black crappie *Pomoxis nigromaculatus*	▲ Largemouth bass *Micropterus salmoides*	Tule perch *Hysterocarpus traski*	Prickly sculpin *Cottus asper*	Staghorn sculpin *Leptocottus armatus*	◆▲ Starry flounder *Platichthys stellatus*
Amphipods *Corophium*	●	●	●	●	○	⬢	◐		⬢	●	●	●	●	◐		●		●	○	●	◐	◐	○
Asiatic clam *Corbicula*			⬢		○					⬢	⬢	○	●			⬢				○			
Oligochaetes *Limnodrilus* *Ilyodrilus* *Peloscolex*			○																				
Mud crab *Rhithropanopeus*	◐	◐	◐									○		○									
Polychaetes *Neanthes* *Boccardia* *Manayunkia*	⬢	⬢	○													○				⬢		○	○
Clams *Macoma* *Mya*			●																				○
Isopods *Synidotea*		○	◐	○								○		○		○		○		○	○	○	
Aquatic insect larvae *Chironomidae*			⬢		○		◐			○	○	◐	○	○		○		◐	○	○	○	⬢	○

● — Greater than or equal to 50% of diet or a major component.
◐ — Important, approximately 20%.
○ — Eaten in small or unknown quantity
⬢ — Rarely eaten
◆ — Species part of a commercial fishery
▲ — Species part of sport fishery

RELATIVE SIGNIFICANCE OF BENTHIC INVERTIBRATE AS PREY ITEM IN THE DIETS OF VARIOUS DELTA CONSUMER SPECIES

Palaemon macrodactylus (Siegfried et al., 1978, Siegfried, 1980; Sitts and Knight, 1979).

Other species of benthic invertebrates have been recorded in diet studies, although less often than Corophium (see Figure 21). Some other benthic organisms that play a role in the Delta-estuarian food web are:

- The estuarine mud crab, Rhithropanopeus harrisii, larvae of which are consumed by shrimp, sturgeon, and striped bass (Eng, 1975; L. Miller, pers. comm.; PGandE, 1981).

- Corbicula, which are eaten by catfish, sunfish, shad, and white sturgeon (Turner, 1966; Eng, 1975).

- Other clams typical of saltier environments, such as Macoma balthica and the isopod Synidotea laticauda, eaten by adult sturgeon (Ganssle, 1966; McKechnie and Fenner, 1971).

- Aquatic insect larvae (primarily Chirononomidae), commonly found in the more freshwater reaches of the interior Delta and sloughs, eaten by many Delta fish (Turner and Kelley, 1966).

Benthos may be eaten by other vertebrates as well. Table 5 shows shore and marsh birds of San Francisco Bay that feed on benthos. Neanthes succinea, a polychaete worm, and the clams Mya arenaria and Macoma balthica are collected in Suisun Bay and occasionally the western Delta. Shore birds may extract benthos from mudflats or shallow channel banks exposed by low tides in the upper estuary.

In the interior Delta, marsh birds and other vertebrates (racoons, for example) may eat clams and worms accessible in shallow waters.

Table 5

INTRODUCED INVERTEBRATES RECORDED FROM BIRD STOMACHS IN SAN FRANCISCO BAY

(Reproduced From Carlton 1979)

PREY	PREDATOR													
	CB	LS	RD	CR	SPP	BBP	W	WSP	LSP	RK	DU	DO	MG	A
Polychaeta Neris succinea					x	x	x	x	x	x	x	x	x	x
Mollusca														
Ischadium demissum				x			x				x			
Gemma gemma					x	x	x	x	x	x	x	x	x	x
Mya arenaria	x													
Mya arenaria and Macoma balthica						x	x		x		x	x		
Tapes japonica							x							
Ilyanassa obsoleta		x	x	x	x	x	x	x	x		x	x	x	x

x = Which species of invertebrate were eaten by which predator species.

PREDATORS:

CB, Canvasback, Aythya valisineria
LS, Lesser Scaup, Aythya affinis
RD, Ruddy Duck, Oxyura jamicensis
CR, Clapper Rail, Rallus longirostris
SPP, Semipalmated Plover, Charadrius semipalmatus
BBP, Black-bellied Plover, Pluvialis scuatarola
W, Willet, Catoptrophorus semipalmatus
WSP, Western Sandpiper, Calibris minutilla
LSP, Least Sandpiper, Calidris mauri
RK, Red Knot, Calidris canutus
DU, Dunlin, Calidris alpina
DO, Dowitcher, Limnodromus sp.
MG, Marbled Bodwit, Limosa fedea
A, American Avocet, Recurvirostra americana

Nutrient Cycling

Another important role benthos may play in the Delta and estuarine food chain, which has not been investigated locally, is the recycling of nutrients through the aquatic ecosystem. Many benthos are opportunistic detritivores. Small bits of organic material such as bacteria, the feces of other benthos, plankton, and decaying plant and animal matter are obtained from the sediments or filtered from the overlying waters and metabolized. Dense populations of benthic organisms may prevent allocthonous and autochthonous organic material from being lost from the system (Brinkhurst, 1972). Because of their methods of burrowing, feeding, and egesting material on the substrate surface, benthic organisms may be instrumental in processing suspended materials and the substrate and releasing nutrients back into the water column (Cherry et al., 1980b). Kraeuter (1976) suggested that biodeposition by benthos could stabilize sediments, retain nutrients and trace elements, and contribute to nutrient recycling of organic materials in the detrital food chain.

Irrigation of sediments by burrowing benthos (clams, amphipods, tubificid worms) may facilitate passive nutrient recycling. Water moving through spaces between sediment particles can cause nutrient diffusion. The presence of tubificid worms has been observed to significantly enhance denitrification and nitrification between water and sediments in laboratory tests. Chatarpaul et al. (1979) and Cherry et al. (1980) suggest that burrowing results in a greater surface area for diffusion of nitrate-diffusion of nitrate-rich water to denitrification sites (including bacteria on or in worms) as well as the enhancement of nitrate in overlying water from worm metabolites.

Kipuchi and Kurihara (1977) also concluded that tubificids facilitated an exchange of dissolved substances. Davis (1973 and 1974a) found that pH was decreased in the upper sediment layers and increased in the lower layers by the presence of worms. Phosphate exchange between sediments and overlying water was increased. As much as one-third of the particulate phosphorus was removed by the marsh mussel _Modiolus demissus_ and deposited where it was utilized by other marsh organisms (Kuenzler, 1961).

Dense oligochaete populations were associated with a greater depth of sediment mixing (Krezoski et al., 1978; Davis, 1974b). Decomposition of organic material and sediment deposition can create a large biochemical oxygen demand. Tubificids, including _Limnodrilus hoffmeisteri_, increased the depth of the oxidized zone in the substrate by 0.3 to 1.6 centimeters in laboratory experiments (Davis, 1974a).

The behavior of burrowing benthos also appears to actively enhance nutrient recycling. The surface sediments may be aerobic, but food material is often derived from the anaerobic layer and deposited at the surface. Chironomid larvae were reported to feed on organic detritus in the sediments (Williams and Hynes, 1974). Brinkhurst (1972) and Brinkhurst et al. (1972) found that the feces of three tubificid worms (_Limnodrilus hoffmeisteri_, _L. udekemianus_, and _Peloscolex multisetosus_, all present in the Sacramento-San Joaquin system) contained as much or more organic matter, nitrogen, and calories than the mud they ingested. This indicated that they were selecting material from within the lower sediments to eat and enriching the surface sediments through fecal deposition. Davis (1974b) suggested that one group's feces that were organically enriched could provide food for other benthic scavengers or bacteria. Deposition of this material at the surface may release nutrients into the water column (Brinkhurst, 1972) and enhance turnover of organic materials formerly lost to the sediments.

The burrowing, filter feeding, and egestion/deposition activities of many benthic organisms may enhance the carrying capacity of the habitat for other species by improving substrate quality as well as nutrient availability. Substrates high in fine particles and organic material support denser, more speciose, benthic communities (Krezoski et al., 1978; Crumb, 1977; Edmonds and Ward, 1979).

Dames et al. (1980) reviewed information on the contribution of filter feeders to nutrient availability and habitat quality. Significant amounts of both sediment and nutrient particles were shown to be processed and made available by many filter feeding estuarine species. In North Inlet estuary in South Carolina, oysters (*Crassotrea virginica*) were calculated to be capable of pumping almost 70 percent of a tidal prism (Dames et al., 1980). Prokopovich (1969) observed that sections of the Delta-Mendota Canal with dense populations of *Corbicula fluminea* contained more sediments than did segments with few clams. Clams deposited 5.4 grams of clastic sediment per year per gram of wet clam weight. Typical *Corbicula* densities found in the Delta-Mendota Canal by Eng (1977) were 10,000 to 20,000 per square meter. Virnstein (1979) noted that substrates with large populations of the polychaete worm *Streblospio benedicti* had higher concentrations of fine silt and clay due to biodeposition. This species has been found at densities of about 1,000 per square meter in the Sacramento-San Joaquin estuary (refer to Figure 10).

Krezoski et al. (1978) calculated that at oligochaete densities of about 1,500 to 3,600 per square meter, biodeposition would exceed the natural sedimentation rate at two localities studied in Lake Huron. Cammen (1980) estimated that a population of the polychaete worm *Nereis (Neanthes) succinea* in a North Carolina salt marsh (mean worm biomass = 1.0 to 3.0 grams ash-free dry weight) ingested about 5 kilograms dry weight of sediment per square meter per year. This was equivalent to turning over the top 2 millimeters of sediment four times each year. The standing crop of worms (number per square meter) and the area of the marsh were not given in this study.

The major taxa collected within the DWR monitoring area met or exceeded densities reported in the literature. Thus, the benthos may contribute to enriching and refining the substrate, enhancing the capacity of the habitat to support larger, more varied invertebrate communities, and returning nutrients to the water column where they can be used by primary producers.

Chapter 5. CONCLUSIONS

In this evaluation of selected water quality parameters and benthic populations, the Department of Water Resources monitoring program produced information that facilitated the characterization of general seasonal and regional patterns of benthic species distribution and abundance over a broad area of the Delta and upper estuary. No direct causal relationships were established, but it is hoped that future studies can examine some of the hypotheses and general patterns discussed in this report.

Throughout the monitoring area, benthic populations underwent an annual increase between May and November. Peak densities were usually observed in June and July. The western Delta supported the highest benthic population densities in the monitoring area. The predominant organisms were amphipods of the genus *Corophium*. The greater temporal variability of the salinity regime in this region is believed to limit colonization to only the most euryhaline or motile species of benthos. The high primary productivity of the entrapment zone probably provides a superabundance of food and other particulate material required by tube-building *Corophium*. Thus, lacking a diversity of competitors, only a few species are able to reach extremely high densities in this region.

Benthic communities of the interior Delta had a greater species diversity but lower densities than similar communities in the western Delta. Even under drought conditions (1976-1977), the more stable salinity regime of the interior Delta appeared to provide favorable habitat for the persistence of diverse, abundant benthic populations. This area is removed from the direct impacts of large freshwater outflow and salinity changes that affect the western Delta and Suisun Bay. Therefore, the interior Delta may be an important reservoir of adult benthos stocks. Following environmental perturbations such as drought or flood, which reduce benthos populations, the interior Delta may supply large numbers of immatures, which can rapidly recolonize favorable habitat downstream within their salinity tolerances.

Changes in the benthic community can be associated with fluctuating water quality conditions. Salinity appeared to be influencing benthic population distribution and density. The dominant euryhaline taxa in the sampling area appeared to be adversely influenced by intense short-term salinity fluctuations (large flood outflows, etc.) or by prolonged salinity increases. Dry conditions in 1976, 1977, and again in 1981 seem to have had the greatest impact on benthos of the western Delta. *Corophium* numbers decreased, allowing temporary colonization by saltwater-adapted species from San Pablo Bay.

Differences in benthic populations were also assessed in relation to substrate composition and relative current velocity. Regions with either very slow or very rapid currents supported the lowest benthic population densities. Rapid current velocities were clearly unfavorable to most benthos, because high flows can remove substrate and benthic stocks. Very slow currents could also be detrimental, because they may transport insufficient detrital materials for the dominant species of surface-dwelling, encrusting, or tube-building benthos. Other species adapted to obtaining raw materials from within the substrate may actually be favored by these conditions. Ideal current velocities cannot be determined from data available at this time.

Flooded tracts, shallow river channels, and the banks of deeper channels are generally exposed to more moderate currents. They provide a mixed substrate and probably sufficient nutrients to support the largest, most diverse, and persistent benthic communities. These localities may also provide a more favorable habitat for supplying colonizers by sheltering benthos from the worst effects of scouring floodflows or salinity intrusion. When advantageous flow conditions return, benthos appeared able to disperse from protected areas and quickly reestablish large colonies.

The role of benthos in the Delta food chain, though not well studied, may at times become significant. When other food items are not available, Corophium may become important to young striped bass. The significance of benthos in the diets of salmonids and other native Delta fish is not well understood.

The importance of Delta benthos in nutrient recycling is unknown, but they may play a significant role by returning nutrients that have been buried in the sediments to the water column, thereby making them available to primary producers. Studies in other delta-estuarine environments suggest that the feeding and burrowing of benthic invertebrates may enhance food web productivity in shallow waters by:

° Irrigating the substrate and allowing water to dissolve nutrients out of the sediments.

° Consuming organic material buried in the sediments and releasing it back to the water column through fecal deposition and egestion.

° Enhancing habitat (substrate) quality for other benthos through biodeposition and bioturbation.

Information collected by DWR and other studies reviewed in this report indicates that many benthic species possess traits that facilitate their survival and rapid recolonization after temporary, short-term perturbation. Many species have short life cycles (one to two years), short maturation periods (less than one year), and rapid growth rates. They produce abundant young between spring and fall. The predominant species within the DWR monitoring area are euryhaline and can withstand all but the most extreme salinity fluctuations. In addition, water circulation patterns in the system probably facilitate dispersal of immatures over a wide area of the estuary.

Operations of the State Water Project and Central Valley Project can potentially affect benthic populations by (1) affecting seasonal salinity patterns during periods of export, (2) determining localized current velocities and substrate composition during pumping plant operations, and (3) transporting large numbers of pelagic larvae or juvenile benthic organisms throughout the system, both downstream and upstream, during water export.

In the western Delta, stabilization of seasonal salinity intrusion may extend the geographic area and time period in which other select benthos species could survive and reproduce, such as the freshwater-adapted species Corophium stimpsoni. This could benefit the food web by extending food supplies for the higher trophic levels. The growth of dense benthos aggregations in this region may also enhance primary productivity by returning nutrients to the aquatic environment.

The relationship between water export, current velocities, and benthic population densities is not clearly understood. There may be an optimum current velocity (as yet undetermined) that provides adequate influx of necessary particulate and nutrient material but does not remove substrate and benthic stocks. For example, comparing substrate composition and average benthic population density at Franks Tract

(D19), a flooded tract, with that of a conveyance channel in Old River (D28A right bank) shows that the location with a more mixed substrate typical of somewhat higher velocities (D28AR) typically supports more invertebrates than does the site with slower velocities (D19). The left bank at Old River (D28AL) has a more sandy substrate typical of faster currents, and population densities average somewhat lower than at the right bank. The substrate composition and benthos densities at Mossdale on the San Joaquin River (C7), which has more rapid current velocities during water exports, suggest a reduction of the density and diversity of benthic populations due to removal of fine substrate particles or the organisms themselves.

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Appendix A

SUMMARY OF BENTHIC ORGANISMS OBSERVED DURING MONITORING PROGRAM[1/]

Scientific Name	Sampling Stations																		
	C3	C7	D4	D6	D7	D8	D9	D10	D11	D12	D14A	D16	D19	D24	D26	D28A	MD6	MD7	PB
PROTOZOA																			
Spongillidae																			
Spongilla sp. A																			
COELENTERATA																			
Hydridae																			
Hydra sp. A	X																		
Campanulariidae																			
Obelia sp. A																			
Clavidae																			
Cordylophora lacustris																			
PLATYHELMINTHES																			
Planariidae																			
Dugesia tigrina													X			X	X		
Unknown triclad A				X															
Unknown triclad B			X						X				X						
NEMERTEA																			
Unknown Paleonemertea sp. A			X		X		X		X										
Tertestemmatidae																			
Prostoma graecense (rubrum)			X						X		X		X			X	X		
NEMATA																			
Plectidae																			
Eudorylaimus sp. A	X	X	X	X	X				X	X	X		X	X	X	X	X	X	X
Unknown Nemata sp. A	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X
ECTOPROCTA																			
Lophopodidae																			
Pecinatella magnifica																			X
Fredericellidae																			
Fredericella sultana																			
Paludicellidae																			
Paludicella articulata																			
Plumatellidae																			
Stolella indica																			
Unknown cheilostomata																			
ENTOPROCTA																			
Pedicellinidae																			
Barentsia benedeni																			
Urnatellidae																			
Urnatella gracilis																			
ANNELIDA																			
Naididae																			
Chaetogaster cristallinus									X										
C. diastrophus																			
Dero sp. A	X												X				X	X	X
Nais simplex																			
N. pardalis																X	X	X	
N. variabilis																			
Pristina breviseta		X														X	X	X	
Slavina appendiculata		X							X				X		X	X			
Vejdovskyella intermedia									X	X			X		X	X	X	X	
Wapsa mobilis			X						X							X		X	
Tubificidae																			
Branchuira sowerbyi	X	X	X							X	X		X				X	X	X
Aulodrilus pluriseta			X										X			X			
Ilyodrilus frantzi			X						X							X	X	X	X
I. templetoni			X				X		X		X		X			X	X	X	X
Limnodrilus angustipenis																			
L. hoffmeisteri	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
I. udekemianus			X													X			
Peloscolex gabriellae	X			X							X	X		X	X	X		X	X
Psammoryctides multisetosus		X																	
Spirosperma ferox																			
Tubificid sp. C																X			
Enchytraeidae																			
Enchytraeid sp. A																X			
Enchytraeid sp. B																			

1/ Total samples for all years by site through December 1981 shown by X. The list of scientific names has been updated to include all species observed up through 1984 and with appropriate nomenclature corrections. The occurrence of species collected and added to the list after 1981 is not shown in this appendix.

Scientific Name	C3	C7	D4	D6	D7	D8	D9	D10	D11	D12	D14A	D16	D19	D24	D26	D28A	MD6	MD7	P8
	Sampling Stations																		
Lumbricidae																			
Lumbricid sp. A			X						X		X		X	X	X	X	X	X	
Lumbriculidae																			
Lumbriculus variegatus																			
Branchiobdellidae																			
Cambarincola sp. A											X								
Glossiphoniidae																			
Helobdella stagnalis																	X		
Erpobdellidae																			
Dina parva																X			
Spionidae																			
Boccardia ligerica			X	X	X		X	X	X										
Streblospio benedicti				X	X		X												
Cirratulidae																			
Cirriformica spirabrancha																			
Capitellidae																			
Heteromastus filiformis				X	X														
Phyllodocidae																			
Eteone californica				X	X														
E. lighti			X	X	X		X	X											
Polynoidae																			
Harmothoe imbricata				X															
Nereidae																			
Neanthes limnicola	X	X	X	X			X	X	X	X	X		X	X	X	X	X	X	X
N. succinea			X	X	X		X	X	X										
N. procera					X														
Goniadidae																			
Glycinde armigera			X	X	X														
Sabellidae																			
Manayunkia speciosa	X			X 2/							X 2/		X	X	X	X	X	X	X
ARTHROPODA																			
Unionicolidae																			
Unionicola sp. A																X		X	
Unionicola sp. B																X			
Daphnidae																			
Daphnia pulex			X						X				X			X	X		X
Simocephalus serrulatus																			
Chydoridae																			
Eurycercus lamellatus																X			
Sididae																			
Sida cristalline			X										X			X	X	X	
Latona setifera													X				X		
Leptodoridae																			
Leptodora kindtii																X	X		X
Cypridae																			
Stenocypris longicomosa			X						X		X		X	X	X	X	X	X	
Eucypris sp. A			X																
Candonidae																			
Candona sp. A									X				X			X			
Temoridae																			
Epischura nevadensis																	X		
Eurytemora sp. A			X		X				X				X			X			
Cyclopidae																			
Mesocyclops edax			X						X				X			X	X	X	X
Ameiridae																			
Nitocra sp. A			X						X				X						
Balanidae																			
Balanus improvisus			X	X	X		X	X	X										
Unknown family																			
Cumella vulgaris				X															
Tanaidae																			
Tanais sp. A								X											
Idoteidae																			
Synidotea laticauda			X	X	X			X	X										
Asellidae																			
Asellus occidentalis																X	X		
Sphaeromatidae																			
Gnorimosphaeroma lutea																X			X
Ampeliscidae																			
Ampelisca milleri			X	X	X	X	X	X						X					

2/ Presence at these stations doubtful because these are the only instances where this freshwater species was found west of D19 in non freshwater habitat.

Appendix A (Continued)

Scientific Name	C3	C7	D4	D6	D7	D8	D9	D10	D11	D12	D14A	D16	D19	D24	D26	D28A	MD6	MD7	P8
Corophiidae																			
Corophium aescherusicum			X	X	X	X	X	X											
C. oaklandense				X															
C. spinicorne	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
C. stimpsoni	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Grandidierella japonica			X	X	X		X	X	X										
Phoxocephalidae																			
Paraphoxus milleri				X		X								X					
Pleustidae																			
Parapleustes pugettensis			X	X	X			X							X				
Paramoera mohri			X	X															
Gammaridae																			
Anisogammarus ramellus			X																
Talitridae																			
Hyallela azteca																X			
Caprellidae																			
Caprella sp. A				X															
Palaemonidae																			
Palaemon macrodactylus			X	X	X		X		X										
Crangonidae																			
Crangon franciscorum					X	X		X	X										
Astacidae																			
Pacifasticus sp. A	X																		
Xanthidae																			
Rhithropanopeus harrisii			X	X	X		X	X	X		X		X	X					
Baetidae																			
Baetis bicaudatus															X				
Heptageniidae																			
Heptagenia rosea	X																		
Leptophlebiidae																			
Paraleptophlebia sp. A																X			
Ephemeridae																			
Hexagenia limbata californica																	X	X	X
Tricorybtidae																			
Tricorythodes sp. A																			
Gomphidae																			
Gomphus o..ivaceous	X		X						X									X	X
Naucondae																			
Ambrysus sp. A																			X
Hydropsychidae																			
Hydropsyche sp. A	X																		
Hydroptilidae																			
Hydroptila sp. A																X			
Oxyethira sp. A																X			
Leptoceridae																			
Nectopsyche gracilis																			
Chaoboridae																			
Chaoborus albatus		X															X	X	X
Chironomidae																			
Procladius sp. A		X	X								X		X			X	X	X	X
Tanypus stellatus	X	X																	
Chironomus attenuatus	X	X	X						X		X			X		X	X	X	X
Cryptochironomus sp. A	X	X	X					X		X			X		X		X		X
Demicryptochironomus sp. A	X	X	X							X		X		X	X				
Endochironomus sp. A			X																
Parachironomus sp. A	X									X								X	X
Harnischia curtilamellata	X	X	X							X			X	X	X		X	X	X
Paracladopelma sp. A	X		X											X	X	X	X		
Paratendipes sp. A	X	X												X			X		
Polypedilum sp. A	X	X	X													X			X
Robachia claviger	X																		X
Stictochironomus sp. A			X																
Einfeldia sp. A																			
Atanytarsus sp. A																			
Cladotanytarsus sp. A	X	X														X			X
Micropsectra sp. A																			
Monodiamesa sp. A																			
Epoicocladius sp. A																			
Nanocladius distinctus																			
Psectrocladius sp. A			X													X			
Cricotopus bicinctus																			
Unknown orthoclad pupae																			
Ceratopogonidae																			
Palpomyia sp. A									X							X	X	X	

Scientific Name	Sampling Stations: C3	C7	D4	D6	D7	D8	D9	D10	D11	D12	D14A	D16	D19	D24	D26	D28A	MD6	MD7	P8
MOLLUSCA																			
Planorbidae																			
Gyraulus sp. A															X				
Gyraulus sp. B																X			
Rissoidae																			
Barleeia sp. A				X	X														
Pyramidellidae																			
Odostomia fetella				X	X		X												
Mytilidae																			
Musculus senhousia				X	X		X												
Corbiculidae																			
Corbicula fluminea	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sphaeriidae																			
Musculium sp. A																			
Tellinidae																			
Macoma balthica			X	X	X		X	X											
Veneridae																			
Protothaca staminea				X	X														
Myidae																			
Mya arenaria			X	X	X	X	X		X										
Unionidae																			
Anodonta nuttalliana																X			
CHORDATA																			
Molgulidae																			
Molgula manhattensis				X	X														